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VULNERABILITY OF UNDERGROUND POL STORAGE FACILITIES

Hans R. Fuehrer, et al

Orlando Technology, Incorporated

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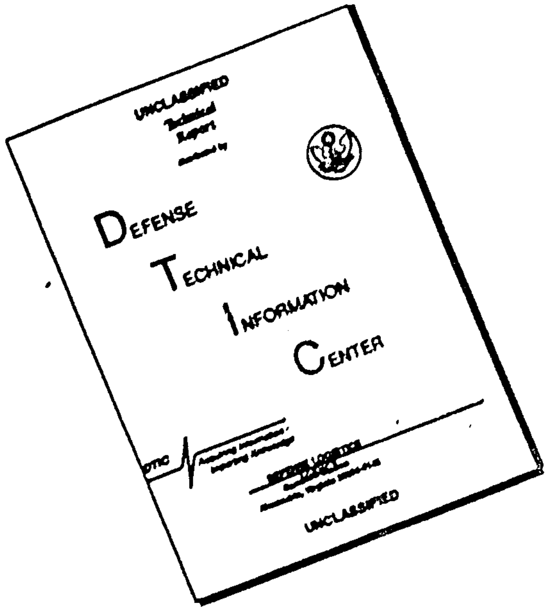

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Hans R. Fuehrer

John W. Keeser, Jr.

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ORLANDO TECHNOLOGY, INCORPORATED

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AIR FORCE ARMAMENT LABORATORY

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EGLIN AIR FORCE BASE, FLORIDA

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Vulnerability

Of

Underground POL Storage Facilities

Hans R. Fuehrer
John W. Keeser, Jr.

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FOREWORD

This report summarizes analytical and experimental investigation conducted from May 1974 through November 1974 by Orlando Technology, Inc., Orlando, Florida under Contract F08635-74-C-0131, Vulnerability of Underground POL Storage Facilities Study, with the Air Force Armament Laboratory, Armament Development and Test Center (ADTC), Eglin Air Force Base, Florida. Mr. Phillip T. Nash (DLYV) managed the program for the Armament Laboratory.

The report contains experimental data and analyses of the data to establish the blast vulnerability of underground petroleum/oil/lubricant (POL) storage tanks. Orlando Technology, Inc. Program Manager was Dr. Hans R. Fuehrer, and Mr. John W. Keeser, Jr. was a principal contributor.

This technical report has been reviewed and is approved for publication.

Roy C. Compton

ROY C. COMPTON
Acting Chief, Weapons Systems Analysis Division

ABSTRACT

This report summarizes results of a six-month test and analysis program pertaining to the vulnerability of underground petroleum/oil/lubricant (POL) storage facilities. The objective of this program was to generate basic test data that can be used to evaluate lethality of inventory and developmental warheads against typical underground POL storage facilities. The POL targets were tested using various sizes and configurations of buried explosives charges against one-third scale target tanks both filled and partially filled with jet fuel. Twenty-nine subsurface detonations and one above-surface detonation test were conducted. Data were generated for various size charges as a function of stand-off distance of the explosive charge from tank center. Variations in charge location were also incorporated. Test results showed that coupling of the burning detonation products to the fuel ejection spray obtained from the tank after rupture is required if a fire is to be initiated. An explosive charge of 8.75 pounds was the minimal value for fire ignition with the one-third scale tests. Below this threshold value, explosive charges would cause tank damage, but fuel ignition or sustained fires would not occur. Above this weight, fire-starting stand-off distances could be increased with increasing explosive weight. However, the exact stand-off distance had to be defined in terms of the charge position relative to the tank at the time of detonation. The effects of interconnecting piping from tank to tank, incendiary munition debris, and synergistic effects were not considered in this program. It is recommended that additional work be done to investigate the results of variations in these parameters.

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SECTION I

SUMMARY

. PROGRAM OBJECTIVE

This final report summarizes a test and analysis program conducted to generate basic test data that can be used to evaluate the lethality of inventory and developmental warheads against typical underground petroleum/oil/lubricant (POL) storage facilities. POL storage facilities are a critical component of target complexes such as airfields, refineries, transfer stations, port facilities, and other targets. Munition effectiveness and/or target vulnerability of POL facilities are accomplished by defining levels of damage for the target and determining the weapon type required to achieve the desired level of damage. Past efforts in studying POL storage vulnerability have been concerned with either large (greater than 50,000-gallon capacity) above-ground tanks or small (40,000- to 60,000-gallon capacity) tanks. The problem of buried POL storage vulnerability is an extremely complex problem and has been studied only for nuclear weapons against large, underground flexible tanks.

B. PROGRAM APPROACH

The program was phased toward accomplishing the above objectives. In order to investigate and define tank rupture contours and compare with those generated from larger scale models, representative one-third scale model POL storage facilities were constructed for testing. Various sizes and configurations of buried explosive charges were detonated against the POL target tanks both filled and partially filled with jet fuel.

Having correlated the one-third scale damage contours through validation tests, studies of fire propagation mechanisms were initiated. This phase involved experimental and analytical research necessary to develop relations establishing ignition criteria for the jet fuel by the detonating explosive gases.

The combined results of both phases provide a data base for fuel ignition by an underground detonation which is capable of assessing the ignition effectiveness against buried POL targets.

C. PROGRAM RESULTS

Twenty-nine subsurface tests and one above-surface were conducted. Table 1 provides a summary of the 30 tests and results

TABLE 1. SUMMARY OF EXPLOSIVE TESTS AGAINST UNDERGROUND POL TANKS

Test Number	Charge Position[1]	Charge Weight (Pounds)	Fuel Level	Standoff Distance (inches)	Target Setup[2]	Damage Level	Sustained Fire	Comments
1	1	1.1	Full	4	1	Heavy	No	Both tank end plates ruptured
2	1	1.1	Empty	9	1	Slight	No	Tank slightly crushed - no rupture
3	1	8.75	Full	9	1	Heavy	Yes	Both end plates severed - concrete broken
4	1	8.75	Empty	23	1	Slight	No	Tank slightly crushed - no rupture
5	1	1.1[3]	Full	4	2	Slight	No	Tank slightly crushed - no rupture
6	1	1.1[3]	Empty	9	2	Heavy	No	One end plate ruptured - tank crushed
7	1	8.75	Full	17	2	Heavy	No	Severed one end plate - large fuel puddle
8	1	8.75	Full	13	2	Heavy	Yes	Marginal fire, severed one end tore other
9	1	8.75	½ Full	13	2	Heavy	Yes	Marginal fire tank completely crushed
10	1	4.9	½ Full	9	2	Slight	No	Small tears on each end of tank
11	1	4.9	½ Full	4	2	Heavy	No	4½ ft X 2 ft hole in tank
12	1	4.9	½ Full	Contact	2	Heavy	No	1/3 of tank blown away
13	1	8.75	½ Full	Contact	2	Heavy	Yes	½ of tank blown away - remainder crushed
14	1	8.75	½ Full	17	2	Heavy	No	One end plate sheared - slight crush
15	1	7	½ Full	Contact	2	Heavy	No	Both ends severed - ½ central part blown away
16	1	8	½ Full	Contact	2	Heavy	No	½ of tank blown aw[illegible] - tank blown out of crater

TABLE 1. SUMMARY OF EXPLOSIVE TESTS AGAINST UNDERGROUND POL TANKS (CONTINUED)

Test Number	Charge Position[1]	Charge Weight (Pounds)	Fuel Level	Standoff Distance (Inches)	Target Setup[2]	Damage Level	Sustained Fire	Comments
17	1	8	½ Full	4	2	Heavy	No	Both ends severed - tank blown out of crater
18	3	8.75	½ Full	Contact	2	Heavy	No	1/3 of tank blown away - big fuel puddle
19	1	1.5	½ Full	Contact	3	Heavy	Yes	Drum demolished - fire started in old test crater 20 feet away
20	3	8.75	Full	Contact	2	Heavy	Yes	Top 1/3 of tank blown away - bottom perfed
21	4	8.75	½ Full	9	2	Heavy	No	Sheared end & crimped - left 25 gallon fuel in tank
22	4	8.75	½ Full	4	2	Heavy	No	Sheared end - peeled top off tank
23	4	8.75	½ Full	Contact	2	Heavy	Yes	Sheared end - partially crimped tank
24	2	8.75	½ Full	4	2	Heavy	No	Top of tank blown through bottom
25	2	8.75	½ Full	Contact	2	Heavy	No	Blew top half of tank away - sheared both end plates - 20 gallon of fuel left in tank
26	1	15	½ Full	16	2	Heavy	No	Split tank in half - both tanks blown out of crater
27	1	15	½ Full	13	2	Heavy	Yes	Crushed blown out of crater - fire not in crater
28	1	30	½ Full	16	2	Heavy	Yes	End plates left in crater - Crushed tanks blown out of crater - fire not in crater

TABLE 1. SUMMARY OF EXPLOSIVE TESTS AGAINST UNDERGROUND POL TANKS (CONCLUDED)

Test Number	Charge Position[1]	Charge Weight (Pounds)	Fuel Level	Standoff Distance (Inches)	Target Setup[2]	Damage Level	Sustained Fire	Comments
29	4	[illegible]	½ Full	4	2	Heavy	No	Split tank open - sheared end - no fuel puddle
30	1	30	½ Full	24	2	Heavy	No	Blew tank body out of crater - both ends stayed in crater - body crushed

[1] The number refers to explosive position relative to the tank.

1. Midtank Horizontal
2. Midtank 45 Degree
3. Midtank Vertical
4. End-tank Horizontal

[2] The target setup refers to the tank configuration.

1. 4-tank array with concrete
2. 2-tank array without concrete
3. 55-gallon drum above ground

[3] Charge cased in steel pipe section.

of each. Composition C-4 explosive charge weights ranged from 1.1 to 30 pounds. Since these tests were one-third scale, full scale charge weights of 30 pounds to 810 pounds were evaluated.

A minimum threshold value of 8.75 pounds (full scale-235 pounds) of explosive was established for achieving sustained fire. Tests with 8.0-pound (full scale-216 pounds) charges did not produce fires. Further, the threshold value of 8.75 pounds was valid only for certain charge positions relative to the target tank periphery. The most vulnerable position of those tested existed when the charge was detonated opposite the tank center in a horizontal plane. As the charge was moved closer to the end of the tank or to a higher elevation, the distance between the charge and tank had to be decreased to obtain a sustained fire. The threshold charge started sustained fires at a 13-inch stand-off when detonated in the horizontal plane opposite the tank center. This charge had to be placed in contact with the tank to obtain a sustained fire when detonated in the horizontal plane at one end of the tank. A sustained fire was obtained against a full tank but not a half-full tank when the 8.75-pound threshold charge was detonated on the center-top of tanks.

Full tanks tended to provide sustained fires more often than half-full tanks due to the dispersion of a greater amount of fuel spray or mist and due to more fuel remaining in the crater. This observation led to the use of half-full tanks as the standard for comparison.

Near-empty tanks were also tested. These tanks contained one gallon of jet fuel. No ullage detonations or fires were observed with these tests as evidenced in aircraft fuel tanks perforated by both penetrater and HEI projectiles.

From a study of all the test data, the following conclusions were drawn:

1. Large munitions are required to start sustained fires when attacking underground POL tanks. The bare charge equivalent weight should be in excess of 235 pounds of Composition C-4 explosive.

2. Fuze setting should be made to provide the largest crater possible. Both ends of the target tank should be uncovered so the fuel spray and detonation products may interact sufficiently to produce a sustained fire.

3. For any weapon to start a fire, the target tank must fall within the crater and (a) have both ends of the tank ruptured sufficiently to produce a fuel spray, or (b) have the tank translated sufficiently that fuel dispersion occurs as the tank translates.

RECOMMENDATIONS

The following recommendations are made as a result of this effort:

1. Review methods of piping and pumping fuel from the storage containers to other points and conduct a series of tests to establish the effect of pipe rupture and fuel spillage therefrom, and the probability of fuel ignition as a result of these rupture points.

2. Review tie-down techniques for the fuel tank to conduct tests to establish the effect of container restraints on tank ejection from the crater area and subsequent fire ignition.

3. Conduct a series of tests to establish synergistic effects when one warhead ruptures a tank without igniting a sustained fire and a second warhead provides an energy source for subsequent ignition of the spilled fuel.

4. Conduct a detailed theoretical and experimental investigation into dynamic scaling effects in fire ignition and propagation.

5. Investigate the effect of incorporating incendiary material into munitions with regard to dispersing these incendiary particles and causing fires to start in fuel-filled craters.

REPORT ORGANIZATION

Section II of this report presents the test procedures used throughout the program including target and charge descriptions, data reduction techniques, and instrumentation employed. Section III discusses in detail the test series providing summary and typical photographs of tests. Section IV is a summary of the test results, including variations in charge position and effects of fuel levels within the tanks. Appendix A contains the test data sheets with two photographs each of the test results and discussions of scale modeling techniques.

SECTION II

TEST PROCEDURES

The purpose of this section is to present a general description of the targets, test setups, explosive devices, and data collection techniques used during the course of the program. This discussion will, in turn, make the detailed test series presented in Section III easier to interpret and employ.

A. TARGET

The petroleum/oil/lubricant (POL) test array used in this program is discussed below. This description includes the tanks, set-up, concrete work area, fuel used, and modifications to the initial setup.

1. Target POL Tank

The target POL tanks used for all underground tests were one-third scale models of typical fuel storage tanks. Figure 1 presents a photograph of a tank while Figure 2 is the design drawing. Salient design points are:

a. The tank was of all-welded construction.

b. All tanks were constructed from 11-gauge hot rolled mild steel sheet per ASTM specification A415. This gauge steel sheet has a thickness range of 0.119 to 0.127 inch and is generally referred to as 1/8 inch.

c. The main cylindrical portion of the tank was cold rolled to the two-foot diameter with the longitudinal seam butt welded using E7018 electrodes. Two passes, one on each side of the joint, were made to insure weld integrity.

d. The circular end plates, flame cut, were inserted into the ends of the cylinder and fillet welded along their circumference. This efficient method of construction was found to be extremely satisfactory.

e. A fill pipe with threaded cap was fillet welded to the tank near one end. The number of pipes used varied from one to four for each tank.

2. Underground POL Setup

In the initial testing, four tanks with concrete work areas

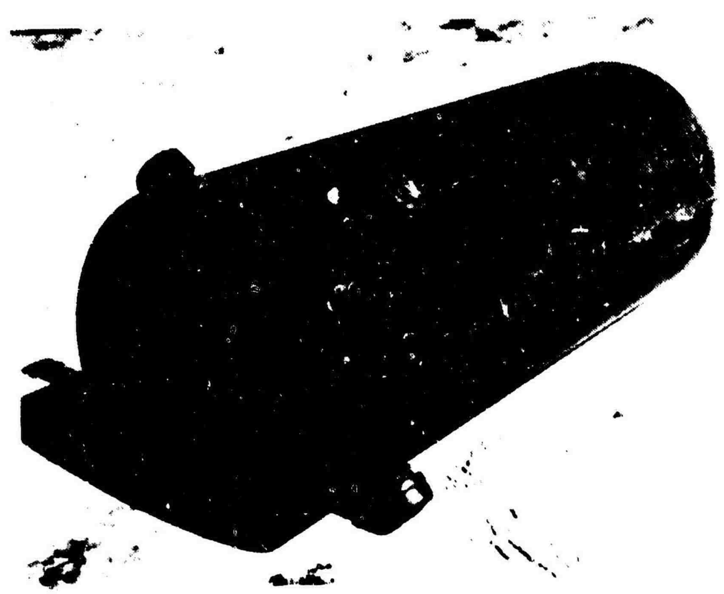
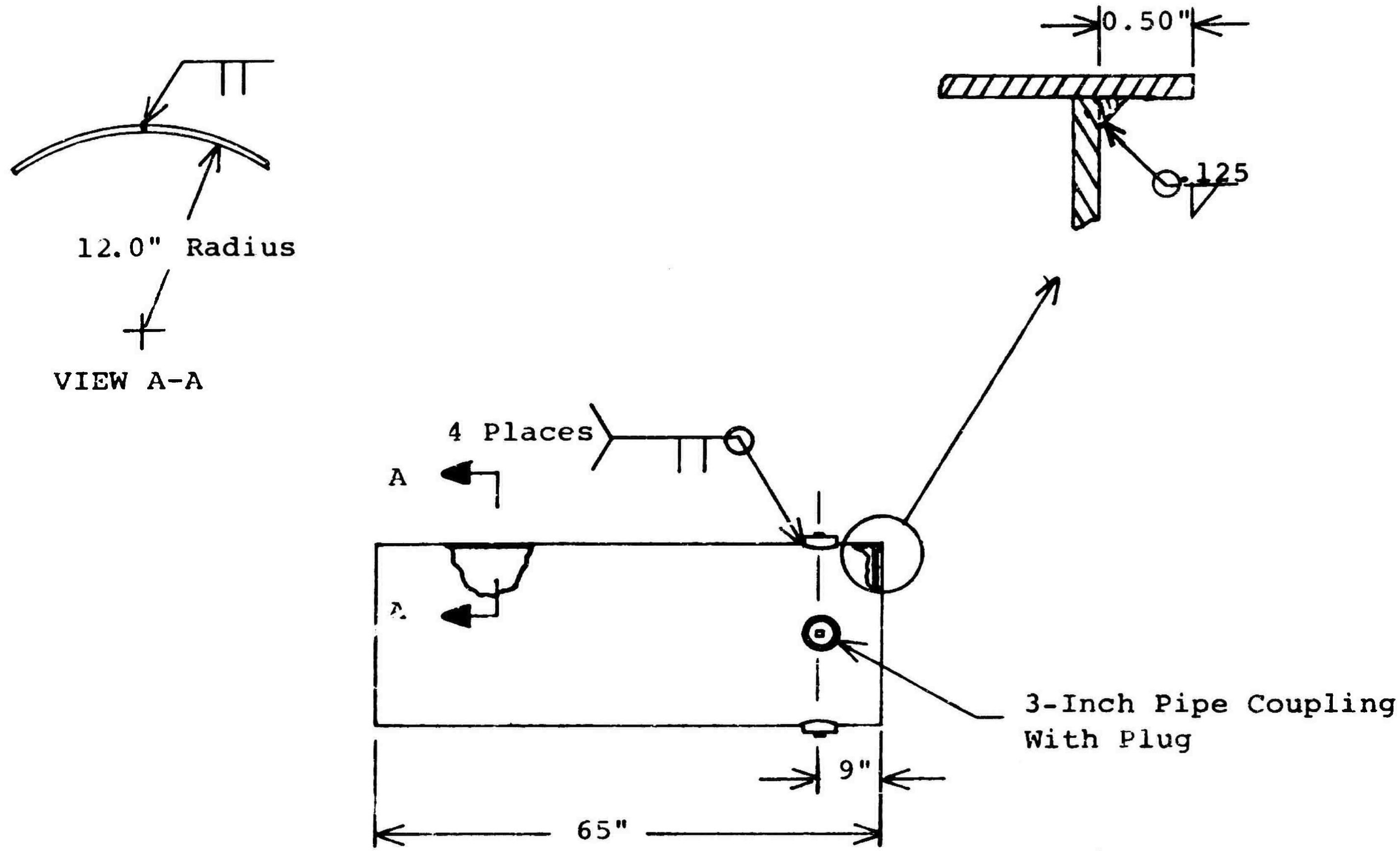


Figure 1. Typical Steel Fuel Storage Tank



Fuel Tank

MATERIAL HR STEEL 11 GAUGE

Figure 2. Assembly Details of Steel Storage Tank

were buried to simulate a POL storage area. A sketch of the first test configuration is shown by Figure 3. Figures 4 and 5 are photographs of an actual test site.

These sites were prepared by using a tractor with front-end loader attachment to dig out the area. Wooden tank supports (2 per tank) were then placed in the proper location. These supports insured that the tanks remained in their proper relative locations when the soil was back-filled. The longitudinal axis of each tank was placed 32 inches away from and parallel to its neighbor. This gave 8 inches of space between the tank walls. The ends of the tanks were placed 9 inches apart. After all the tanks had been emplaced and leveled, the soil was packed around the tanks so as to leave no voids or soft areas. The weight of the water-filled tractor tires was used to compact the soil. The filling continued until the soil just covered the tanks. The excavation had been made in such a way that the upper surface of the tank array was even with the undisturbed ground level. Two concrete work areas were then emplaced. Afterwards, filling and packing resumed. The finished site had a 13-inch-high dirt mound over the tanks and extending out from the tank array 10 feet in all directions. The mounds were also packed by repeatedly driving the tractor over the top.

3. Concrete Work Area

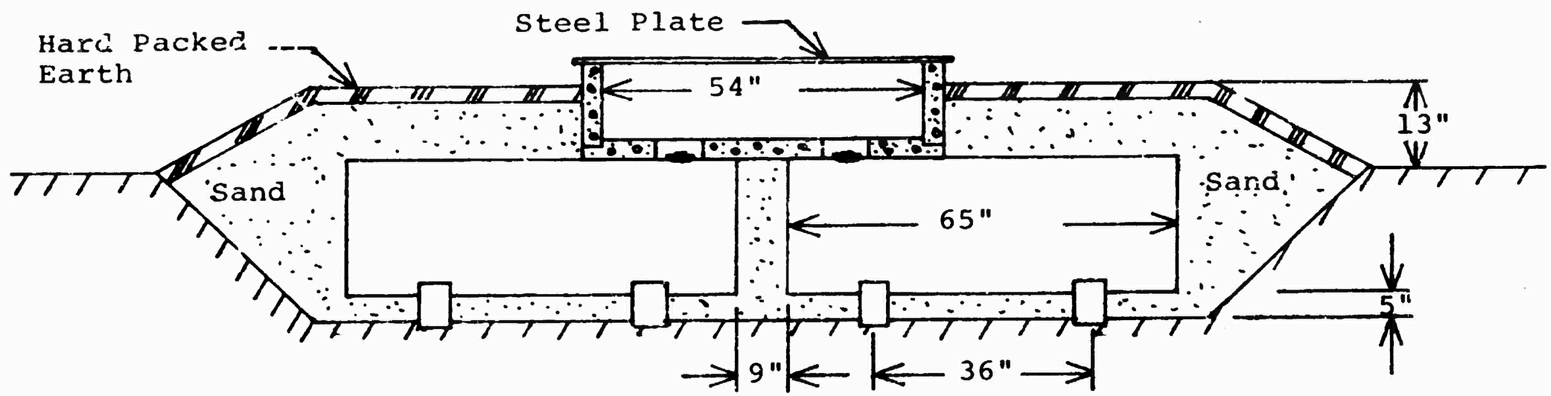
In order to simulate the pumping and inspection areas of an actual POL storage area, it was necessary to build a reinforced concrete sump which was placed between the fill pipes of two tanks. Figures 6 and 7 are plans for the components used while Figures 8, 9, and 10 show individual items prior to assembly.

The main components of these work areas were access ports for each fuel tank, interlocked steel bar corners, and a 1/8-inch-thick steel cover for each work area. Figures 11 and 12 show a test set-up using the concrete work areas. The fill was packed around and between the two areas.

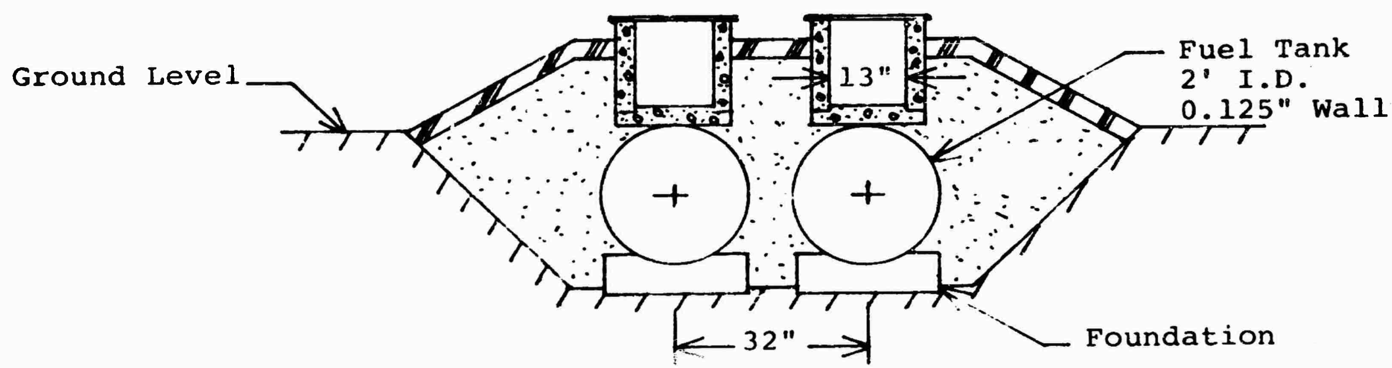
4. Target Fuel

In all of the tests, jet A-1 fuel was used. This fuel is a commercial, kerosene-type jet fuel with a freezing point depressant added. A complete fuel analysis was conducted by the Aerospace Fuels Laboratory at MacDill Air Force Base, Florida. Table 2 gives these test results.

These results showed that the fuel used met the criteria of specification number ASTM-D-1655.



SIDE VIEW



END VIEW

Figure 3. Side and End Views of Buried POL Site

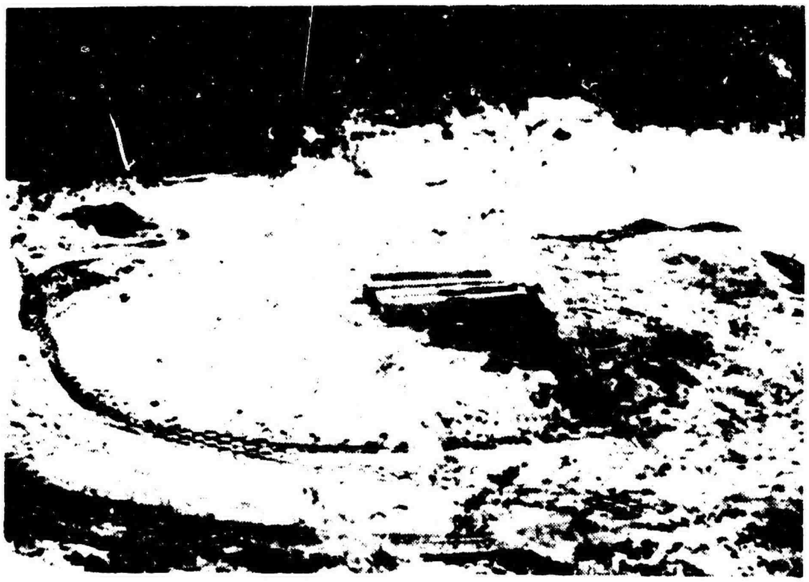


Figure 4. Overall View of Typical POL Test Site

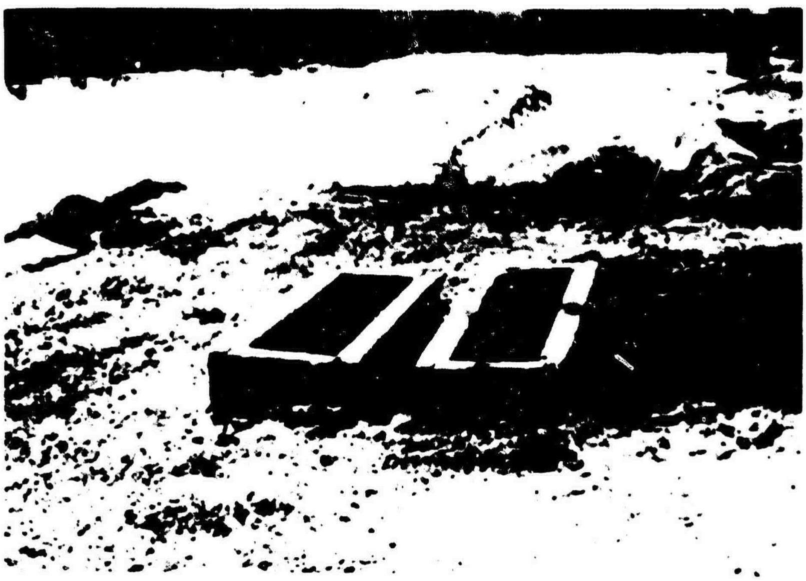


Figure 5. Closeup of Concrete Work Area Without Steel Plate

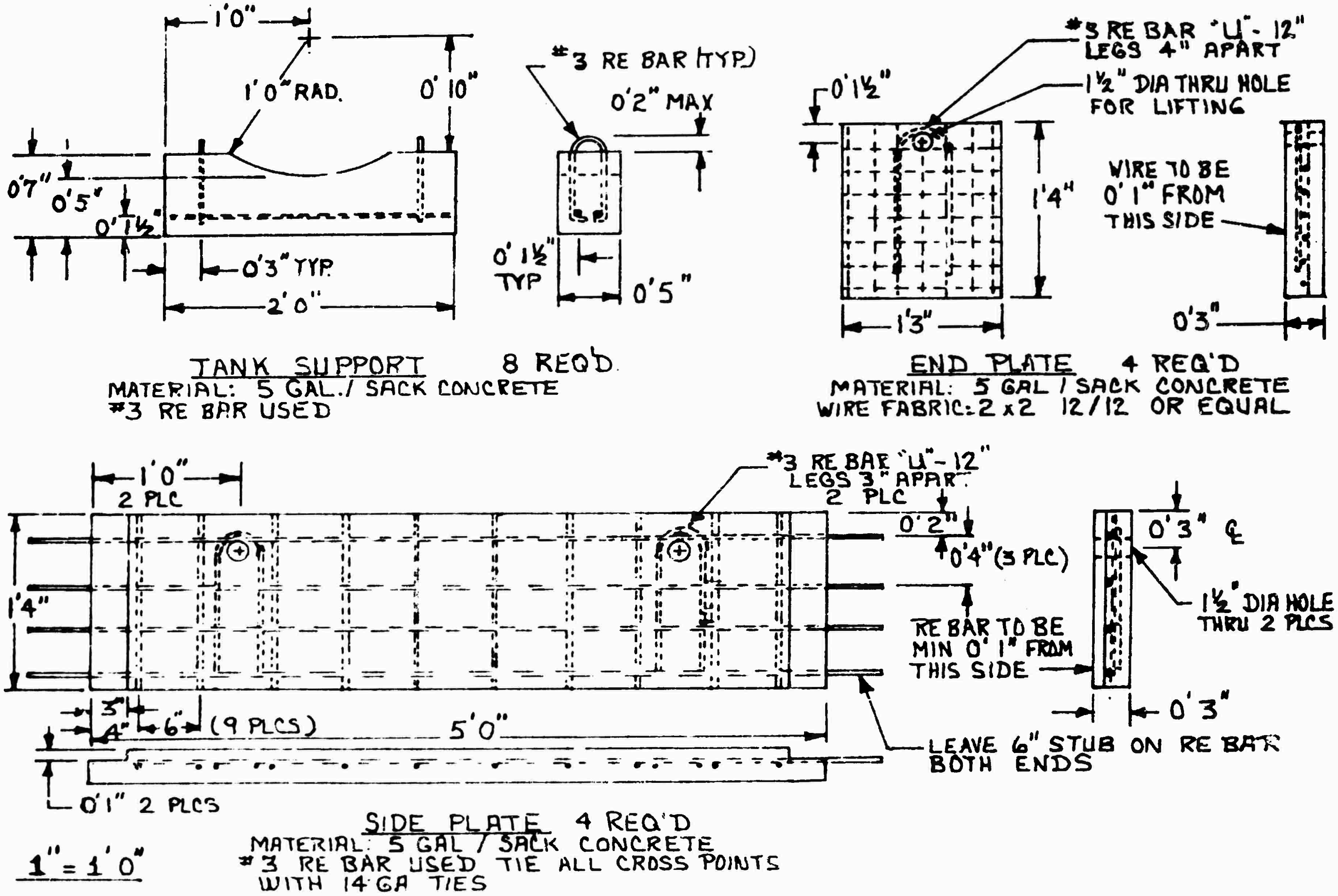


Figure 6. Concrete Work Area, Side and End Details

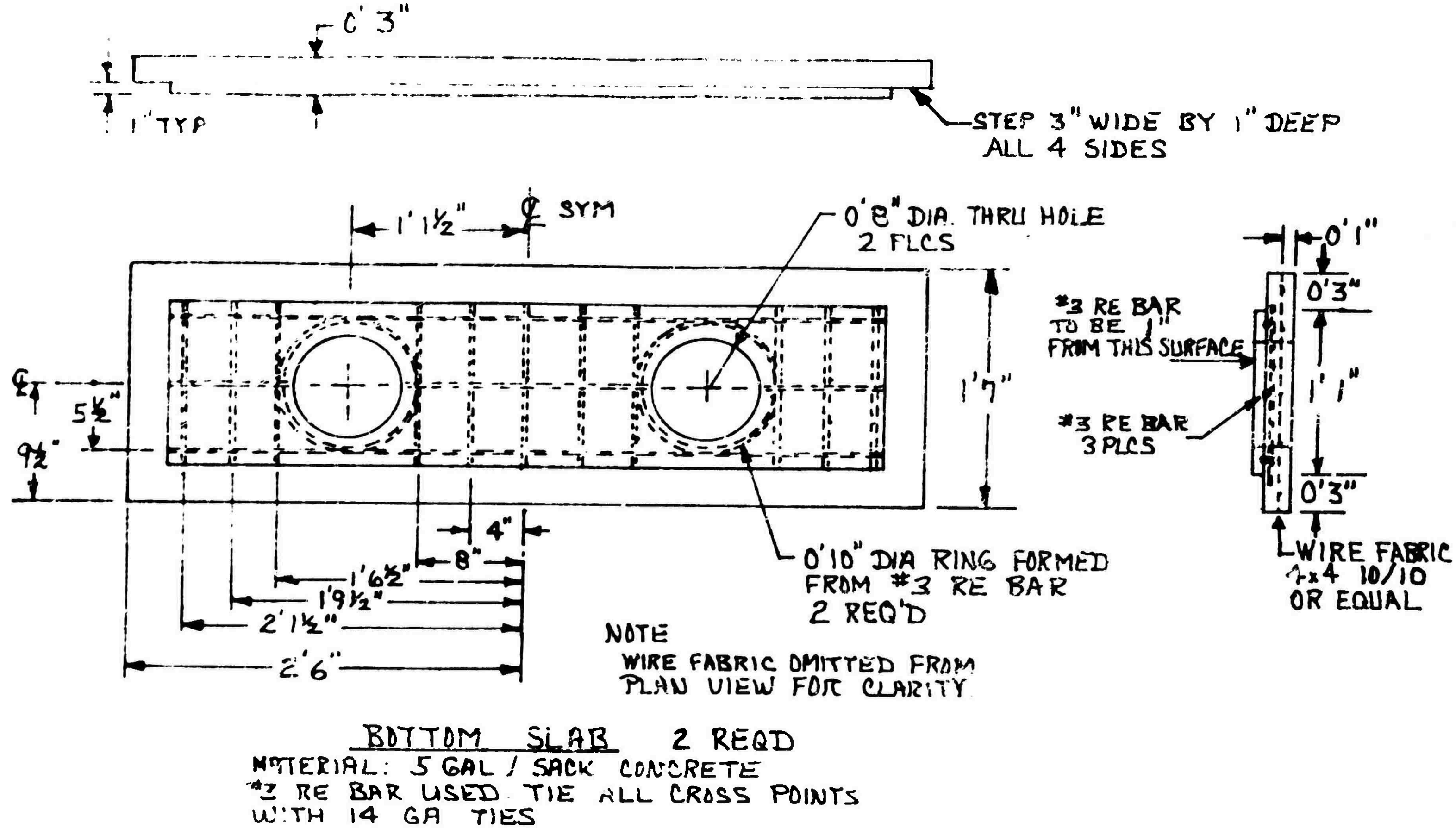


Figure 7. Concrete Work Area, Base Details

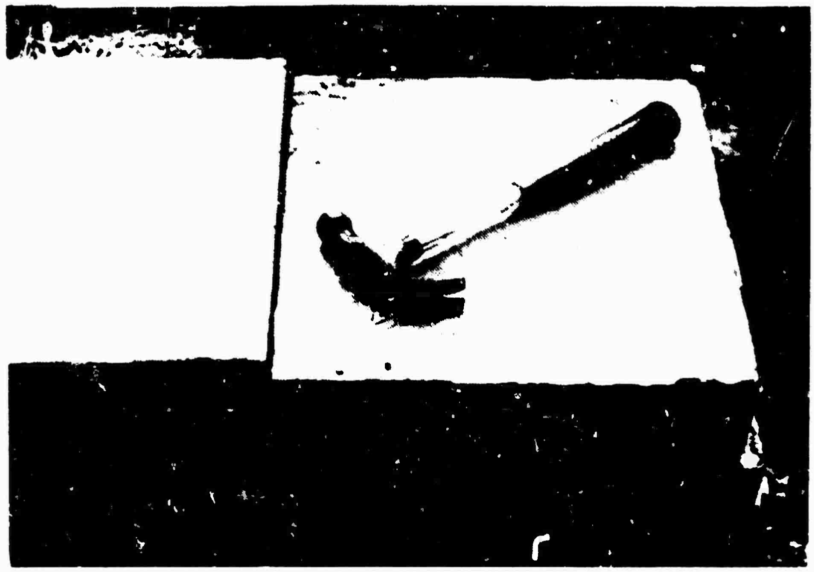


Figure 8. Concrete End Slabs for Work Area

Figure 9. End Detail of Side Pieces for Work Area

Figure 10. Concrete Work Area Base Slab Details

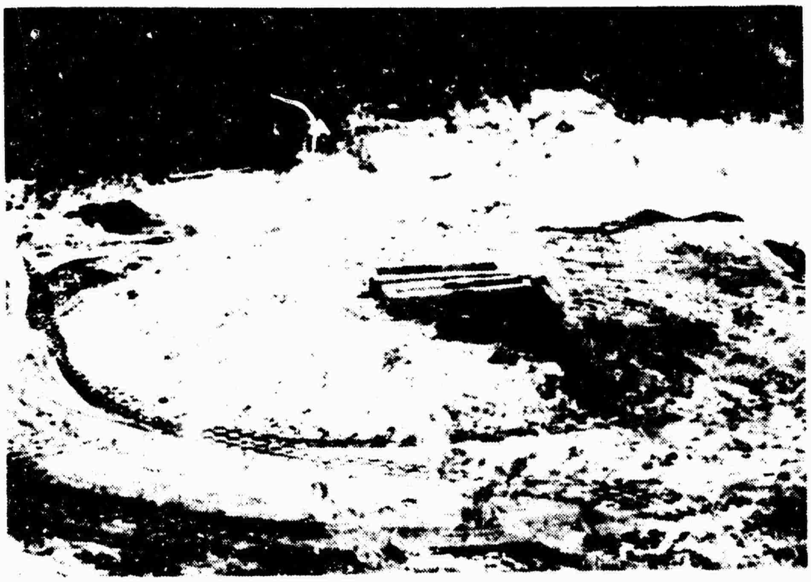


Figure 11. Overall View of Original Test Site

Figure 12. Closeup of Original Test Site

TABLE 2. FUEL TEST RESULTS

Gravity °A.P.I.	42.0	Fire Point COC	175 °F
Specific Gravity 60/60	0.8156	Flash Point PM	144 °F
Vapor Pressure, PSI @ 100 °F	0.20	Freeze Point ≈	-40 °F

DISTILLATION DATA

Initial Boiling Point	358 °F	
10% Vaporized	377 °F	
20% Vaporized	387 °F	
32.5% Vaporized	400 °F	
50% Vaporized	416 °F	
90% Vaporized	469 °F	
98.5% Vaporized	501 °F	(End Point)
1.1% Residue @ End Point		
0.4% Loss		

5. Target Modifications

During the initial validation test series it was found that the concrete work areas were not contributing materially useful data. The work area offered little explosive restraint or damage enhancement to the fuel tanks. Because of their negligible effect, they were deleted from the target setup following Test No. 4.

It was also determined early in the program that two tanks, one immediately behind the other, were sufficient for data purposes. The two tanks to the side of the explosive charge essentially remained undamaged. This was true whether the tanks were empty or full. Figure 13 clearly shows the low damage level sustained by the two tanks not directly in line with the explosive. For this reason all tests after No. 4 had only two underground tanks.

Minor design changes were also made to the test tank during the program. These changes were reduction of number of fill pipes from 4 to 1 and a shortening of the tank from 65 to 60 inches. The first modification was made because damage levels

Figure 13. Minor Damage Level of Offset Fuel Tanks

precluded tank rotation and subsequent re-use. The second change was merely a result of material unavailability. Consistent data was obtained throughout the test program. Hence, these changes were considered minor.

B. TEST ARRANGEMENTS

Three basic test setups were used: a four-tank array, a two-tank array, and a single-above-ground tank.

The four-tank array had the concrete work areas and was used for the first four validation tests. Figures 4 and 5 showed the test setup while Figure 14 is a sketch of the tank identification system used.

The two-tank array consisted of two buried tanks, their long axis parallel and separated by eight inches of soil at their closest point. The tanks were directly behind one another. Soil was compacted to a depth of 13 inches directly over and for a distance

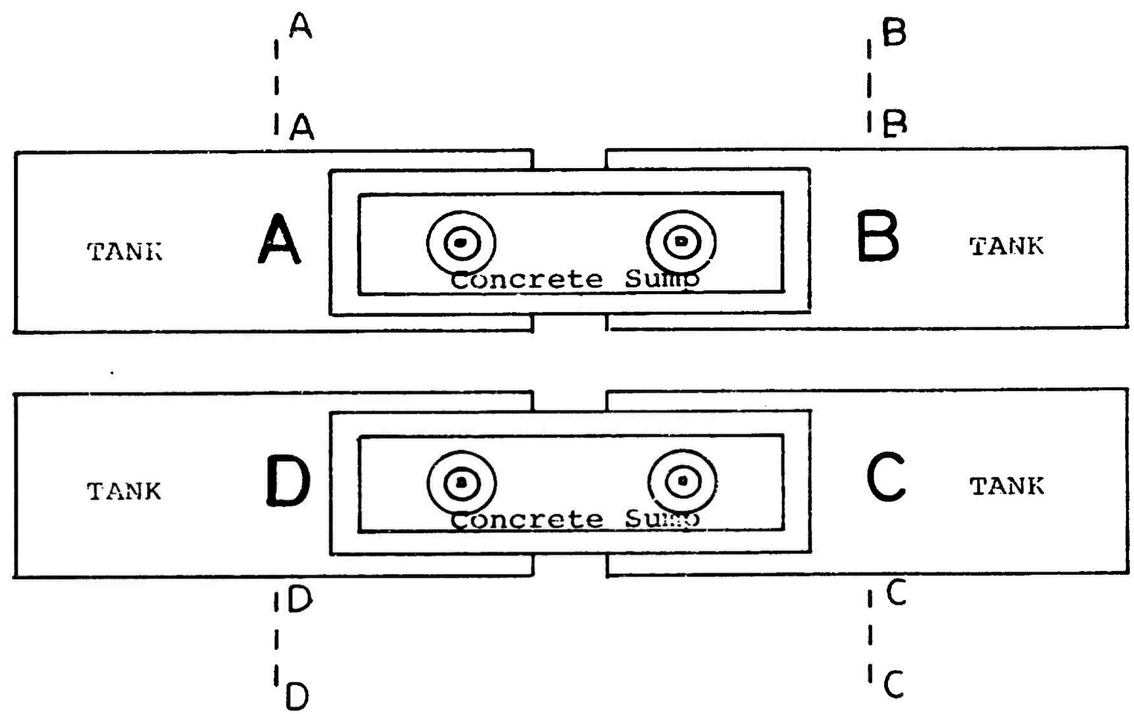


Figure 14. Four-Tank Plan View Test Setup

of 10 feet beyond the buried tanks.

For each of these two test setups, the tank closest to the charge was designated as the "test tank". The tank directly behind it was referred to as the "backup tank". Thus, the axis of the test tank is parallel to the axis of the backup tank, and the explosive charge is placed nearest to the test tank. These were the only tanks which were damaged in the four-tank array, thus enabling use of the more simple two-tank arrangement.

The third test setup was used to illustrate the fire-starting capability of a small explosive charge used against an above-ground tank. For this test a standard 55-gallon steel drum of commercial manufacture was used as the test tank. It was half-filled with fuel, placed on its side on the ground, and a 1½-pound block of explosive taped to the outside at the fuel surface level. Figure 15 is a sketch of the test setup.

C. EXPLOSIVE CHARGE DESCRIPTION

There were three components used in the explosive train:

1. DuPont E-94 blasting caps (13.5 grains of PETN).
2. One hundred grain/foot PETN (Pentaerythritol Tetranitrate) detonating cord with a waterproof cover.
3. Composition C-4 plastic explosive (main charge) which is composed of 91 percent RDX*, 5.3 percent sepacate, 2.1 percent polyisobutylene, and 1.6 percent oil.

The blasting cap was used to detonate the detonating cord which led to the buried mass of C-4. This method was used so that in case of misfire, the blasting cap could be removed easily and safely from the explosive train.

1. Assembly of Explosive Charge

All explosive charges used were solid right circular cylinders with a length-to-diameter ratio of 3. Figure 16 shows a typical charge with detonating cord lead.

The required charge diameter and length for a given weight were calculated as follows:

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* RDX is Cyclotrimethylene Trinitramine

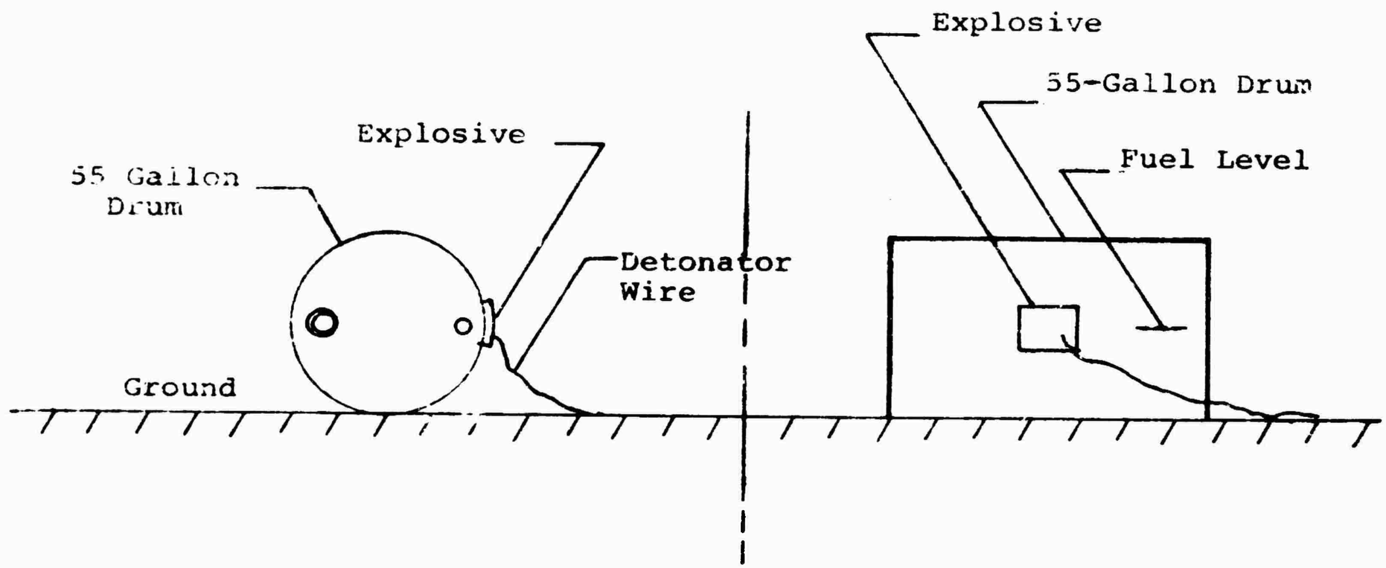

Figure 15. Test Setup for Above Ground Test

$$W = \rho V = \rho \frac{\pi D^2}{4} L \tag{1}$$

ρ = nominal density of C-4 (pounds per in^3)

L = length of cylinder (inches)

D = diameter of cylinder (inches)

V = volume of cylinder (in^3)

W = weight of explosive (pounds).

For a solid right circular cylinder with L/D ratio = 3

L = 3D

ρ = 0.05775 pounds per in^3.

Figure 16. Typical Explosive Charge

Substituting, simplifying, and solving for D gives

$$D = (7.349W)^{1/3} \text{ inches}$$

Using this formula, Figure 17, charge weight versus charge diameter, was constructed. This figure allowed a form to be constructed for any desired charge weight by simply forming a cylinder of length 3D and compacting the preweighed explosive into it.

A standard procedure was followed for making and compacting each charge. The required amount of C-4 was carefully weighed, and then kneaded into a pliable homogeneous mass. The C-4 was then packed into the mold. Particular attention was paid to the elimination of voids in the explosive mass. A six-foot length of detonating cord was used. A stevedore knot was tied in one end and was placed at the geometric center of the charge. The detonating cord was brought through the center of one end of the charge. After the total amount of explosive had been packed, the device was transported to the test site for use. Just prior to emplacement, the molds were removed from the explosive so as not to influence test results. Figure 18 shows a charge emplaced prior to back filling of the hole.

2. Location of Explosive Charge

In the test program four different positions were used for the explosive charge. These were:

Position 1 - midtank horizontal

Position 2 - midtank 45°

Position 3 - midtank vertical

Position 4 - end-tank horizontal.

Figure 19 shows all four positions. All test data sheets in Appendix A reflect these titles when referring to charge location. A brief description of each position follows.

1. Midtank Horizontal

In the midtank horizontal position, the longitudinal axis of the explosive charge and fuel tank were parallel to each other. The charge was located on a horizontal plane passing through the horizontal diameter of the fuel tank. It was equidistant from each end plate of the fuel tank. Standoff distances were measured on a perpendicular from the charge center of gravity to the tank skin.

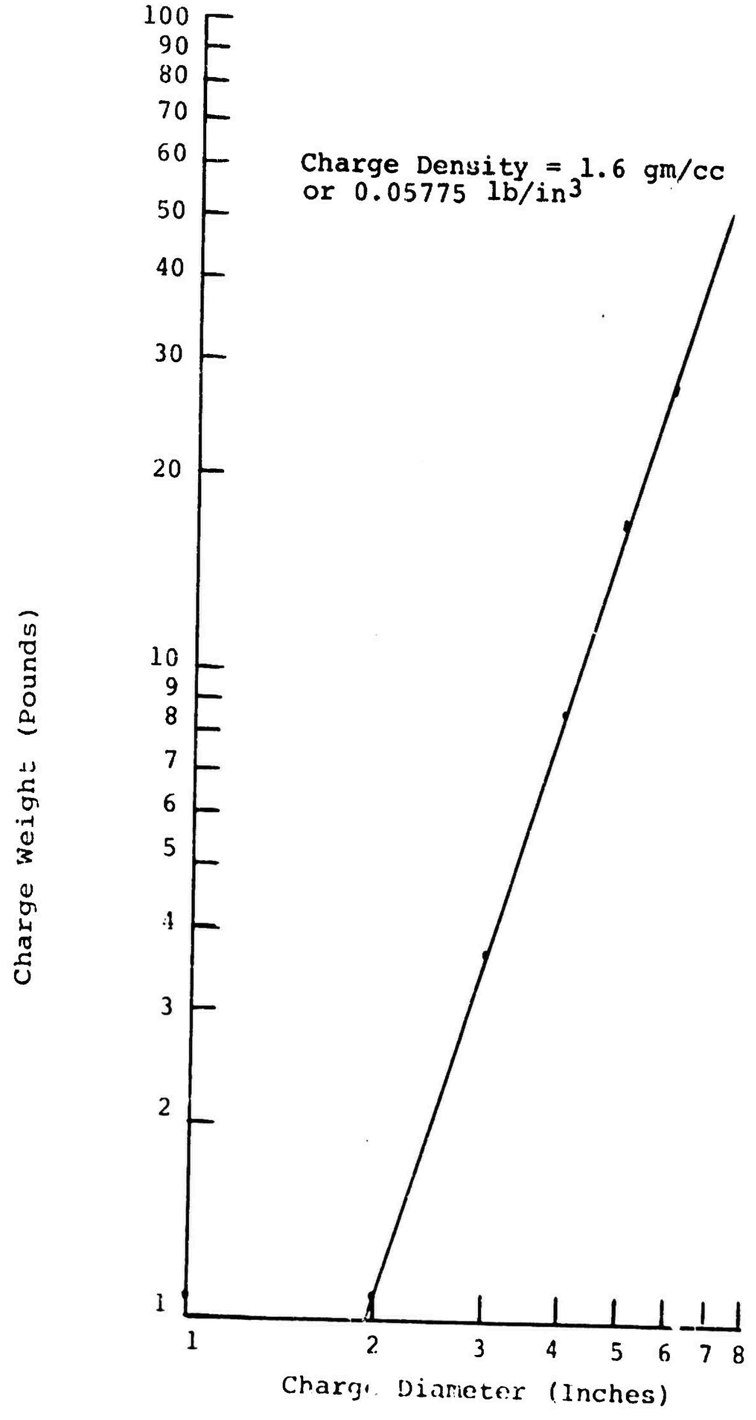

Figure 17. Charge Weight Versus Charge Diameter

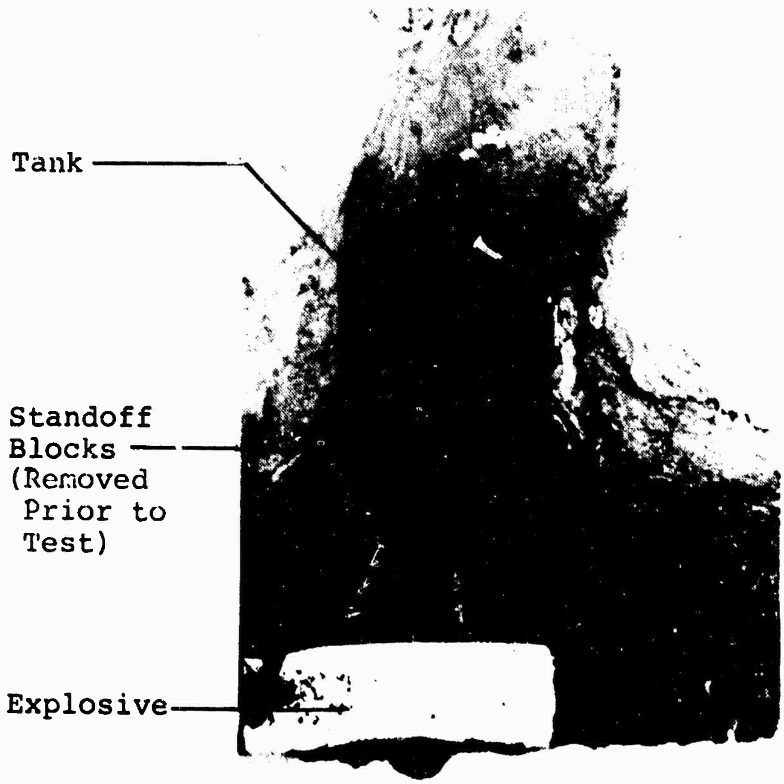

Figure 18. Emplaced Charge With Standoff Blocks

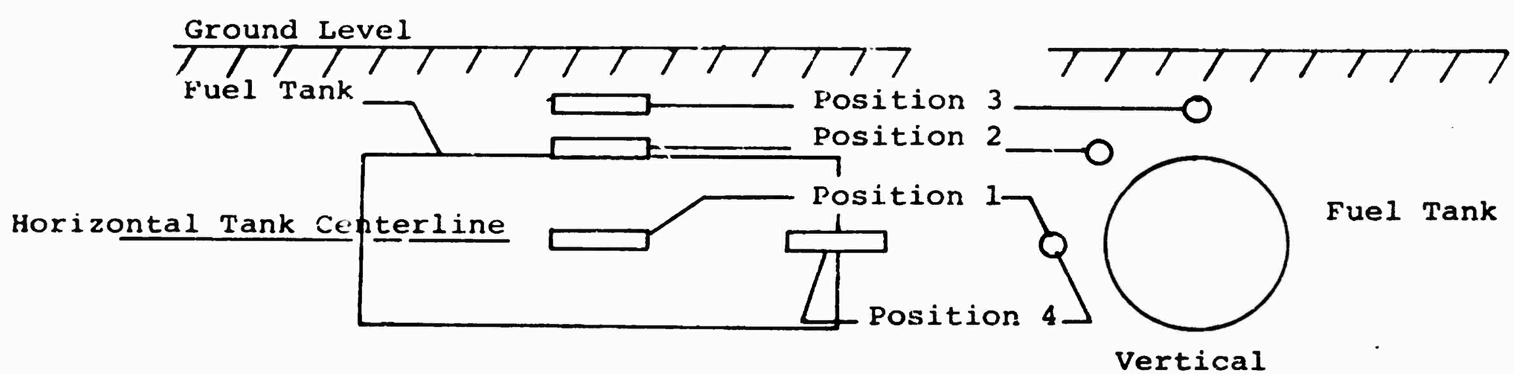

Figure 19. General Explosive Charge Locations

2. Midtank 45°

The only difference between this position and the horizontal position above was that the explosive charge was located on a plane which passed, and was parallel to, the longitudinal axis of the tank at a 45° angle relative to a vertical. All other parameters were unchanged from the midtank horizontal position.

3. Midtank Vertical

In the midtank vertical position, the explosive charge was placed on the longitudinal seam line of the tank. This seam line was directly above the horizontal center line of the tank. All other parameters were unchanged from the midtank horizontal position.

4. End-tank Horizontal

In the end-tank horizontal position, the explosive charge center of gravity was in the plane of the tank end plate. All other parameters were unchanged from the midtank horizontal position.

D. INSTRUMENTATION

Primary instrumentation for the test series consisted of high-speed motion and still camera coverage. All tests were also visible from the firing bunker. The high-speed camera was used to document the detonation and crater-forming portions of the test. The still camera was used for post-test coverage of the crater, tanks, and other significant data items.

The size of the resultant crater and the relationship of the tanks to each other and the crater were carefully noted at the conclusion of each test.

A series of soil samples were also taken periodically throughout the testing sequence for later analysis of moisture content, soil type, and density.

A complete contour plot was generated for the early test tanks to determine the type of crush damage which could be expected later in the test series when larger explosive charges were used.

E. DATA REDUCTION

At the conclusion of a test, the high-speed color film was analyzed to determine interaction points and times between the hot explosive gases and the fuel spray. Fuel spray patterns as a function of charge size and location were also reviewed.

Post-test tank contour and blast damage was studied to determine tank wall failure modes. Both overall blast damage (collapse) and the localized tearing were obtained as the explosive charge size was varied. For certain charge sizes and locations the damage level was so great as to effectively obliterate the tank. Figure 20 shows the remains of tank from Test No. 16.

Figure 20. Extensive Tank Damage Possible Without Fire

When applicable, backup tank translation and damage were documented. This type of damage was more apt to occur at small standoff distances with the charge in the midpoint horizontal position than at other test positions.

The test results obtained in this program can be used for larger systems and tank arrays through the use of the model law. The "model law", when referred to in connection with physical tests, is a term generally applied to a set of rules derived through dimensional reasoning by which the results of a set of properly designed experiments can be extended to larger or smaller scales of phenomena. The term "scale effect" has been somewhat loosely applied to any deviation from the model law that arises in an analysis of experimental results derived from models. The presence of such effects, which apparently do occur in some classes of experiments, greatly complicates the analysis of the results. Fortunately no such effects have been detected in underground explosion testing, and the model law results can be extended with an accuracy as good as that of the original measurements.

If it is assumed that the velocity of propagation of the effect of an explosion in earth depends only on the stress and not on such quantities as the rate of deformation, then the effect of an increase in all dimensions of the experiment by the length scale factor results in an increase of the time of propagation to an equivalent point by the same factor n. It is then possible to make a table (Table 3) in which any quantity, such as pressure, impulse, and velocity, is represented by its dimensional components of mass m, length l, and time t, and to arrive at an expression for the relative magnitude of this quantity in the new system which is expanded in length scale by the factor n. In present experiments $W^{1/3}$, the cube root of the weight of explosive charge, in pounds, has been selected as being a length characteristic of the scale of the experiment. This may seem dimensionally misleading, but it merely means that there has been chosen for reference a unit of length whose cube is proportional to the weight or volume of the charge. Then if an experiment is performed with a charge-weight of W_1 lb and it is required to know the effects that would occur with a charge-weight of W_2 lb, the scale ratio $n = (W_2/W_1)^{1/3}$, and at the distance n, the magnitudes of the quantities in question can be determined from the original measurements at distance r multiplied by the factors given in the table. The model law, of course, tells nothing of the manner in which the quantities vary with distance but states only that if the effect is of magnitude E_1 in the experiment system at a distance r from the charge, then in the new system the effect will be AE_1 at a distance nr from the charge A, depending on the quantity in question and being given in Table 3.

An example that illustrates the us of the model law is the comparison of the peak pressures produce by the explosion of 1 and 1,000 lb of the same explosive. It i assumed that experiment has determined the physical parameters of he 1000-lb charge. The similarity equations can be determined very simply by equating the dimensions on both sides of the equality sign. The variables can be

TABLE 3. COMPUTATIONS OF IDEAL SCALES

Quantity	Symbol	Typical Units	Ideal Scale	
Length	l	ft	l_p/l_m	$= n$
Depth	d	ft	d_p/d_m	$= n$
Area	A	ft^2	A_p/A_m	$= n^2$
Mass	m	$lb\text{-}sec^2/ft$	m_p/m_m	$= n^3$
Area of Rein.	A_s	$in.^2$	$(A_s)_p/(A_s)_m$	$= n^2$
Area of Rein/ft	A'_s	in	$(A'_s)_p/(A'_s)_m$	$= n$
Unit Resistance	w	$lb/in.^2$	w_p/w_m	$= 1$
Total Resistance	R	lb	R_p/R_m	$= n^2$
Weight	W	lb	W_p/W_m	$= n^3$
Distance	r	ft	r_p/r_m	$= n$
Scaled Distance	Z	$ft/lb^{1/3}$	Z_p/Z_m	$= 1$
Total Impulse	I	lb-ms	I_p/I_m	$= n^3$
Unit Impulse	i	$lb\text{-}ms/in.^2$	i_p/i_m	$= n$
Scaled Impulse	$\bar{i}$	$lb\text{-}ms/in.^2/lb^{1/3}$	$\bar{i}_p/\bar{i}_m$	$= 1$
Pressure	p	$lb/in.^2$	p_p/p_m	$= 1$
Kinetic Energy	KE	ft-lb	KE_p/KE_m	$= n^3$
Density	ρ	$lb\text{-}sec^2/ft^4$	ρ_p/ρ_m	$= 1$
Elastic Modulus	E	$lb/in.^2$	E_p/E_m	$= 1$
Deflection	δ	in	δ_p/δ_m	$- n$
Moment	M	ft-lb	M_p/M_m	$= n^3$
Moment/ft	$\bar{M}$	lb	$\bar{M}_p/\bar{M}_m$	$= n^2$
Shear	V	lb	V_p/V_m	$= n^2$
Shear/ft	$\bar{V}$	lb/ft	$\bar{V}_p/\bar{V}_m$	$= n$
Stress	σ	$lb/in.^2$	σ_p/σ_m	$= 1$
Strain	ε	-	$\varepsilon_p/\varepsilon_m$	$= 1$
Velocity	v	ft/sec	v_p/v_m	$= 1$
Time	t	sec	t_p/t_m	$= n$
Moment of Inertia	I	in^4	I_p/I_m	$= n^4$
Frequency	f	cycles/sec	f_p/f_m	$= 1/n$
Acceleration	a	ft/sec^2	a_p/a_m	$= 1/n$

determined from physical considerations, but the manner in which they enter the equation may be determined by dimensional considerations. The form of these equations, of course, needs to be tested against the experimental data in each case and correlated with the first order of approximation. The test for correctness consists in determining to what extent the dimensionless constant in the equations really are constant for widely varying values of the parameters.

This section would be incomplete without a specific mention of target and damage relations to the model law. One of the primary objectives of the program is, of course, to determine the accuracy of the model law as applied to target damage. The chief cause of the initial uncertainty is the fact that there are certain things in nature that do not scale, the chief offender being the effect of gravity. Changes of density of component materials to overcome this defect can be made, but it is not easy to find structural materials of comparable strength and with greatly different densities. Consequently, if gravity is a controlling factor in an experiment, modification of the model law must be made. It has been found experimentally, as had been inferred but not proved, that the impulsive forces involved in the damaging of a structure are very large compared to gravity forces, so that essentially no deviation from the model law was detected. The conclusion is then that the structural dimensions can be scaled, at least over a factor of 5 and probably 10, without encountering any deviation from the law as far as explosive damage is concerned.

It is well known that the development of modeling techniques provides a powerful method for predicting full-scale fire behavior from laboratory tests. Full-scale fires are difficult to control and quantitize and are quite expensive. However, laboratory-scale fires are much easier to control, permit accurate measurements, and cost less per test. From a fire research viewpoint, it is desirable to determine fire behavior through the study of laboratory-scale fires. However, up to the present, it has been difficult to predict the behavior of full-scale destructive fires from a knowledge of small scale fires, since the scaling laws were relatively unknown and the fire behavior itself is frequently influenced by the scale of the fluid dynamics.

It has been known for a long time that one can model full-scale fire convection fluid mechanics with laboratory scale experiments at high pressures. High-pressure modeling with wind tunnel tests is used in the aircraft industry to predict full-scale aircraft behavior. Pressure modeling was used in 1936 in the study of turbulent fire convection. By using pressures up to 65 atmospheres, at a calculated Grashof number of 3×10^{11}, fire convection characteristics of a 370-cm-high, vertical flat plate were obtained using a vertical flat plate only 22 cm high.

More recently, studies have shown that not only steady gas-phase fire phenomena can be modeled, but also the solid phase, heat and mass transfer, fire spread, and other transient phenomena by using the high pressure technique.

To model the fluid mechanics of fires, both the Froude and Reynolds numbers must be reproduced. This is not possible with geometric scaling used in underground shock propagation since the Froude number is the ratio of inertia forces to gravity forces and the gravity term does not scale. The Reynolds number is the ratio of inertia forces to viscous forces and here the viscosity of the fluid does not scale. Hence, one cannot look to the initial dynamic behavior of the test for fire modeling, namely, in the region where gravitational effects are negligible. It is also in this region that the 3000°K detonation products cause ignition of the fuel vapor. Hence, when detonation products mix with fuel vapors, ignition occurs but the need exists to ascertain if a sustained fire will be generated. Thus, in obtaining fire data from the high-speed camera films, emphasis was placed on reviewing the fire characteristics in the turbulent areas. It is here that the fuel vapors are mixed with air, convection heat transfer occurs, and droplet ignition takes place. If heat losses remain less than heat gains, a sustained liquid phase fire will occur.

In summary, it can be said that geometric scaling is acceptable for modeling mechanical behavior of the system under investigation. The fire propagation studies with the geometrical scaling can lead to inconsistencies between the prototype and model work. In the time sequence of events, it is expected that modeling of the ignition process will be inappropriate since the effects do not scale under the conditions tested. However, since detonation products temperature is far in excess of the fuel ignition temperature, it is expected and observed that when the ignition process occurs in the modeling it would also occur in the full-scale prototype. With regard to sustained burning after ignition, the geometrical scaling should provide appropriate data. However, additional work is needed in this area to confirm this hypothesis--namely, the use of scale models in high pressure tanks to ascertain the appropriate scale functions is recommended.

Under the test conditions, geometrical scaling provides good correlation between model and prototype for both mechanical and thermodynamic behavior. The temperature of the detonation products is far above the threshold levels required for ignition of fuel vapors. Sustained burning should be further explored through high pressure modeling techniques.

SECTION III

TEST SERIES

These tests were designed to determine lethality parameters. These parameters were charge location, charge weight, and fuel levels. Validation tests were conducted to correlate one-third scale tests with a larger scale test program. Thereafter, parametric test sequence was conducted. The rationale for the type of tests run and general discussions of each testing sequence are in this section.

All testing for this contract was conducted at the Lady Lake, Florida test facility. The explosive tests were conducted in a 80-foot-diameter arena with 12-foot-high earth walls.

Prior to any underground testing, experiments were conducted to verify the explosive train. The explosive components used were DuPont E94 blasting caps, 100-grain/foot PETN detonating cord, and C-4 plastic explosive. For safety reasons, the detonator was kept above ground level during testing. A six-foot length of PETN detonating cord was end-knotted and buried in the explosive charge. The other end of the detonating cord was left above ground after the charge was buried. The blasting cap was attached to this end. Thus, any misfire or other malfunction would not have required digging up an explosive charge containing a live detonator. (No misfires or hangfire conditions occurred during the program.)

Three breadboard explosive tests were run using 1¼-pound charges with detonators and detonating cord to insure proper operation of the safety interlock system. These tests verified the concept.

A. VALIDATION TESTS

There were six validation tests conducted to establish the dynamic response of the fuel tank array to small explosive charges. These tests were based on data generated at the New Mexico Institute of Mining and Technology against tanks twice the size used in this program. Table 4 is a summary of these validation tests. Appendix A contains detailed data for all tests.

It was found that simulation of the concrete structure used to house intratank piping was unnecessary. Comparison of test craters with and without the concrete showed no difference in shape or size. Figures 21 and 22 show two similar tests with and without the concrete.

TABLE 4. VALIDATION TESTS

Test No.	Charge Weight (lbs)	Stand-off Distance[1] (inches)	Fuel Level[2]	Comments
1	1.1	4	Full	No fire
2	1.1	9	Empty	No fire
3	8.7	9	Full	Sustained fire
4	8.7	23	Empty	No fire
5	1.1	4	Full	Cased charge - no fire
6	1.1	9	Empty	Cased charge - no fire

[1] Measured from skin of tank to center of charge.
[2] Empty tanks contained one gallon of fuel.

Backup Tank: Translation-20 Inches, Vertical Rise-12 Inches

Figure 21. Damage Level with Concrete Work Area
8.75 Pounds at 9-Inch Standoff

Backup Tank: Translation-15 Inches, Vertical Rise-8 Inches

Figure 22. Damage Level Without Concrete Work Area
8.75 Pounds at 13-Inch Standoff

Placing the charge against the centerline of the tank caused large deformation and translation of both the test and backup tanks. Figure 13 clearly demonstrates this translation. The figure also shows little damage to the remaining two tanks in the test array. Since little practical data could be gained from these two tanks, their use was discontinued. The new test array is shown in Figure 23.

Also included in the validation series were two tests using steel-cased explosive charges. These tests, Nos. 5 and 6, were duplicates of Tests No. 1 and 2. Neither test showed shrapnel damage to the fuel tank. The craters were smaller than for the uncased charges, but this was due to the smaller bare charge equivalent explosive available.

It has been experimentally determined that a steel-cased explosive requires a larger weight of explosive than an uncased charge to do equal blast damage. This relationship was shown to be:

$$w = C\left(0.2 + \left(\frac{0.8}{1+\frac{2M}{C}}\right)\right)$$

where: w = bare charge equivalent of cased charge

C = explosive weight in charge

M = weight of case of shrapnel producing agent.

For these tests, 2-inch schedule 40 steel pipe was used as the casing for the explosive.

Solving for the bare charge equivalent weight yielded:

$$w = 1.1\left(0.2 + \frac{0.8}{\left(1+\frac{2(1.82)}{1.1}\right)}\right) = 0.424 \text{ pound}$$

As expected, smaller craters and tank damage levels were obtained with the encased 1.1-pound charges than with the uncased charges.

Comparison of the damage level obtained in these tests with those generated by New Mexico Institute of Mining and Technology (NMIMT) with one-half scale tanks showed extremely good correlation.

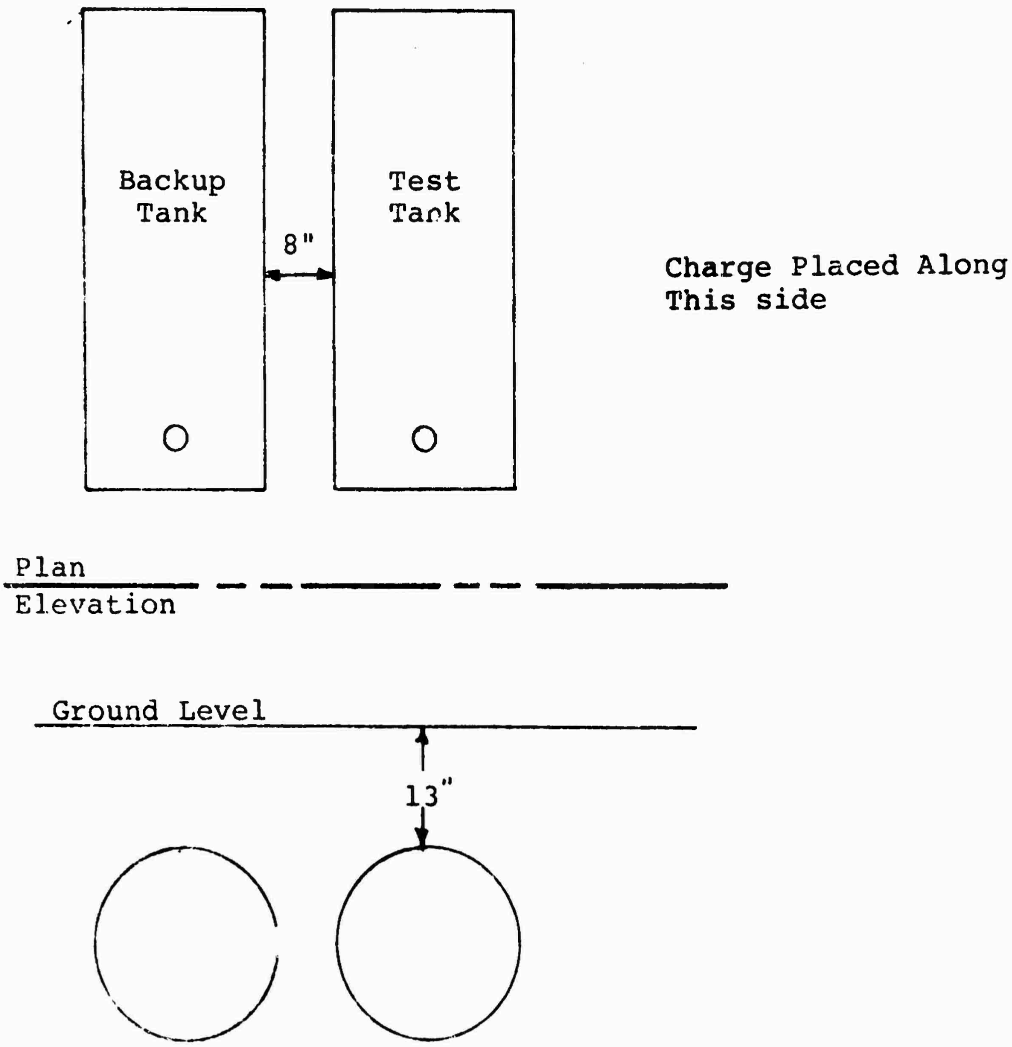

Figure 23. Two Tank Underground Test Array

This was particularly true for deformation of the cylindrical tank surfaces where the same type of continuous collapse was noted as opposed to localized deformation and skin tearing. NMIMT test tanks were bolted together; hence, their skin failure occurred along the upper bolt line.

Conversely, with the welded seam used in this test program, failure occurred just inside the end plates as the fuel pushed the end plates out. Rupture along the end plates resulted in fuel being driven away from the detonation products, thus requiring that fire-starting detonation products extend out further.

The difference in compressibility of the water used by NMIMT and the jet A-1 fuel used in these tests appeared to contribute little to the deformation process.

B. LETHALITY TEST SERIES

Twenty-four tests were conducted to study charge size and placement with regard to fire-starting probability. It was found that midtank vertical and end-tank horizontal charge placements gave very low fire probability regardless of charge size. Table 5 gives the lethality series arranged by position and charge size.

The principal objective of these tests was to cover as large a combination of events as possible, consistent with reliable data. The midtank horizontal series used charges from 4.9 to 30 pounds at stand-off distances from tank contact to 24 inches. An explosive weight of 8.75 pounds constantly ignited fires out to 13 inches. Charge weight of 15 and 30 pounds ignited fires out to 13 and 16 inches, respectively. A total of 18 tests were run using the midtank horizontal position. In addition, 3 tests were run against empty tanks to generate tank data.

Two tests were run using the midtank 45-degree charge position. The 8.75-pound charge was incapable of causing a fire even when in contact with the skin of the tank.

Two tests were also run using the midtank vertical charge position. The 8.75-pound charge started a fire when in contact with the tank skin only when the tank was full of fuel.

Four tests were run with the charge in the end tank horizontal position. A fire was obtained only when the 8.75-pound charge was in contact with the tank skin.

C. LETHALITY TESTS

Analysis of the tests defining the fire-starting parameters of charge size and location are presented in this section.

TABLE 5. FIRE VERSUS CHARGE AND POSITION

Test Number	Explosive Weight (Pounds)	Centerline Distance (Inches)	Fire
	Midtank Horizontal		
5	.464	4	No
1	1.1	4	No
12	4.9	Contact	No
11	4.9	4	No
10	4.9	9	No
15	7	Contact	No
16	8	Contact	No
17	8	4	No
13,20	8.7	Contact	Yes
8,9	8.7	13	Yes
7,14	8.7	17	No
27	15	13	Yes
26	15	17	No
28	30	16	Yes
30	30	24	No
	Midtank Vertical		
18	8.7	Contact	No
20	8.7	Contact	Yes
	Midtank 45°		
25	8.7	Contact	No
24	8.7	4	Flash
	End Tank Horizontal		
23	8.7	Contact	Yes
22	8.7	4	No
21	8.7	9	No
29	15	4	No

1. Midtank Horizontal

There were a total of 22 tests conducted with the charge in the midtank horizontal position. This included the six validation tests. Three of these were against empty tanks, five were against full tanks, and the remainder were against half-full tanks.

The empty tank tests were to determine tank response to the explosive pulse. Table 6 lists applicable test results. In no case did a fire occur, even from ullage fuel fume ignitions.

In general, the response of the empty tank was one of crushing directly in front of the charge and localized tearing near the end plates. The failure near the end plates was a combination of shear failure and bending failure. In these tests and in all comparable tests the end plate failure always occurred behind the weld. This failure was usually accompanied by some necking down of the tank wall. Figure 24 illustrates this form of tank failure.

The 19 tests conducted with the charge in the midtank horizontal position are summarized in Table 7. Figure 25 is a plot of charge size versus standoff distance. Lethality limits are shown by the shaded area. The smallest charge size, regardless of standoff, required for a sustained fire was 8.75 pounds. This was true with both full and half-full tanks. Film analysis indicated flash vapor fires and short (<1 second) vapor explosive interactions when smaller charges were used. From a study of all test data, several necessary fire conditions were found.

a. Both ends of the fuel tank were uncovered.

b. Both ends of the fuel tank were ruptured and/or separated.

c. The crater was at least 48 inches deep.

These conditions may not be all inclusive, but no sustained fire occurred without all of them being present.

The eight tests conducted with the charge in other than the midtank horizontal position indicated a much lower fire probability, all other things being equal. Table 8 is a summary of these tests.

Figures 26, 27, and 28 are plots of charge size versus standoff distance. Again, the cross-hatched area denotes lethality levels.

2. Midtank Vertical

The probability of a fire in the midtank vertical position is

TABLE 6. SUMMARY OF EMPTY TANK TESTS

Test Number	C-4 (Lb)	Standoff (Inches)	Crater Data (Inches)			Tank Crush[1] (Horizontal Centerline)			Tank Translation (Inches)
			Perpendicular	Parallel	Depth	+18 (Inches)	At Charge	-18 (Inches)	
2	1.1	9	65	78	30	6 3/4	11	9 1/4	8
4	8.75	23	180	150	48	14	13 1/4	11 5/8	15
6	0.464[2]	9	48	72	16	2 3/4	9 1/2	12	0

[1] This is the distance in inches that the tank wall deviated from a circle.
[2] This was a steel cased charge. The bare charge equivalent is given.

Figure 24. Typical End Plate Failure Mode

TABLE 7. SUMMARY OF MIDTANK HORIZONTAL TESTS

Test Number	Explosive Weight (Pounds)	Standoff (Inches)	Fuel Level	Tank Ends Uncovered	Crater Data (Inches)			Sustained Fire	Fuel Spray Characteristics	Fuel Puddle	Comments
					Perpendicular	Parallel	Deep				
1	1.1	4	Full	1	72	96	27	No	Fine wide spread mist	yes	Both end plates 2/3 torn off
3	8.75	9	Full	Both	168	168	54	Yes	Bow tie shape	Yes	Fuel spray and fire in crater and tank ends - tank crushed, both ends severed
5	5.464	4	Full	None	57	70	17	No	None	No	No tank failure occurred just crushing
7	8.75	17	Full	Both	144	132	54	No	Behind tank - fine	Yes	Large post test fuel puddle in crater
8	8.75	13	Full	Both	156	132	54	Yes	Bow tie shape	Yes	Fire initiated at tank end - spread to puddle
9	6.75	13	1/2	Both	174	150	54	Yes	Ellipse behind tank	Yes	Fire remained on crater lip - tank lifted out of crater onto rear lip
10	4.9	9	1/2	No	126	126	44	No	None	No	Small splits on each tank end
11	4.9	4	1/2	1	99	106	40	No	Fine mist - large circular area	No	Side of tank blown away - tank rotated 60
12	4.9	Contact	1/2	1	87	96	36	No	60' diameter circle	No	Tank side blown away -one end sticking over crater lip
13	8.75	Contact	1/2	Both	126	132	48	Yes	60' diameter ellipse	No	Fire on crater lip behind tank - side of tank blown away

TABLE 7. SUMMARY OF MIDTANK HORIZONTAL TESTS (CONCLUDED)

Test Number	Explosive Weight (Pounds)	Standoff (Inches)	Fuel Level	Tank Ends Uncovered	Crater Data (Inches)			Sustained Fire	Fuel Spray Characteristics	Fuel Puddle	Comments
					Perpendicular	Parallel	Deep				
14	8.75	Contact	1/2	1	132	140	48	No	Coarse mist around crater	Yes	<5-gallons fuel in puddle - one end plate sheared off
15	7	Contact	1/2	Both	132	126	48	No	40 foot diameter ellipse-coarse spray	No	Both ends severed - body crushed - no fuel left
16	8	Contact	1/2	Both	144	132	42	No	60 X 40 foot ellipse	No	Tank blown out of crater
17	8	4	1/2	Both	132	144	48	No	20 X 10 coarse spray behind crater	No	Both ends blown off - body 20 feet behind crater
19	1.5	Contact	1/2	--	Above Ground			Yes	Oak leaf shape - stem perpendicular to tank	No	55-gallon drum totally destroyed
26	15	16	1/2	Both	192	186	72	No	Triangle with base on crater lip	No	Tank thrown out of crater 30 feet - heavy dirt fall out on tank
27	15	13	1/2	Both	156	150	48	Yes	10 foot rectangle around tank	No	Tank 20 feet behind crater and surrounded by fire - no fire in crater
28	30	16	1/2	Both	186	168	60	Yes	Fine mist over arena area	No	Tank 20 feet behind crater and surrounded by fire
30	30	24	1/2	Both	174	180	72	No	A very fine mist throughout arena		Tank center thrown behind crater 2½ feet - ends remained in crater

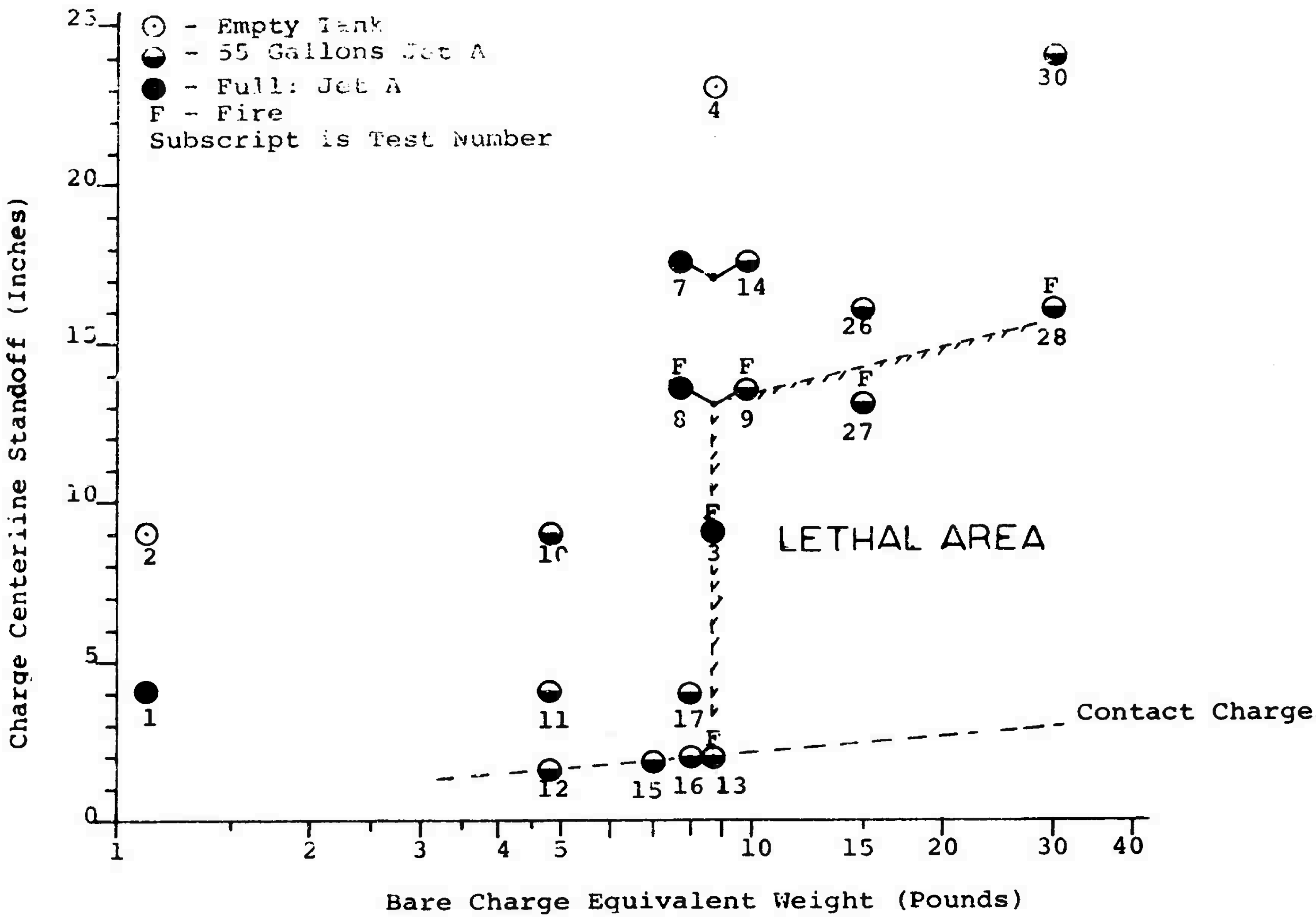

Figure 25. Charge Size Versus Distance for Midtank Horizontal Position

TABLE 8. SUMMARY OF MIDTANK 45-DEGREE, MIDTANK VERTICAL AND END-TANK HORIZONTAL TESTS

Test Number	Explosive Weight (Pounds)	Standoff (Inches)	Fuel Level	Tank Ends Uncovered	Crater Data (Inches) Perpendicular	Parallel	Deep	Sustained Fire	Fuel Spray Characteristics	Fuel Puddle	Location Charge[1]	Comments
24	8.75	4	1/2	No	132	120	24	No	Ellipse around tank	Yes	2	Blew side of tank away - both ends sheared off - flash fire
25	8.75	Contact	1/2	Both	102	120	30	No	Ellipse around tank	Yes	2	20-gallon fuel left in tank - 1/2 of tank blown away
18	8.75	Contact	1/2	No	-	-	-	No	Ellipse around tank	Yes	3	Blew away top center of tank and both end plates - 20-gallon fuel in tank
20	8.75	Contact	Full	Both	128	144	40	Yes	2 lines 60° apart from tank ends	Yes	3	Blew top of tank through bottom - fuel spray 40 feet away burned
21	8.75	9	1/2	Both	-	-	-	No	Line parallel to tank	Yes	4	Tank lifted out of crater and crimped closed - 25-gallons of fuel in tank
22	8.75	4	1/2	1	96	108	48	No	Fan shaped-apex at tank	Yes	4	5-gallon fuel in tank - end nearest charge blown off - far end undamaged
23	8.75	Contact	1/2	1	150	144	44	Yes	Fan shaped	No	4	Near end sheared off - fire confined to fuel spray area
29	15	4	1/2	2	156	168	60	No	Evenly spread	No	4	Far end of tank lifted out of crater - near end blown off

[1] The charge locations are the same as shown in Figure 21.
[2] Midtank 45-Degree
[3] Midtank Vertical
[4] End-tank Horizontal

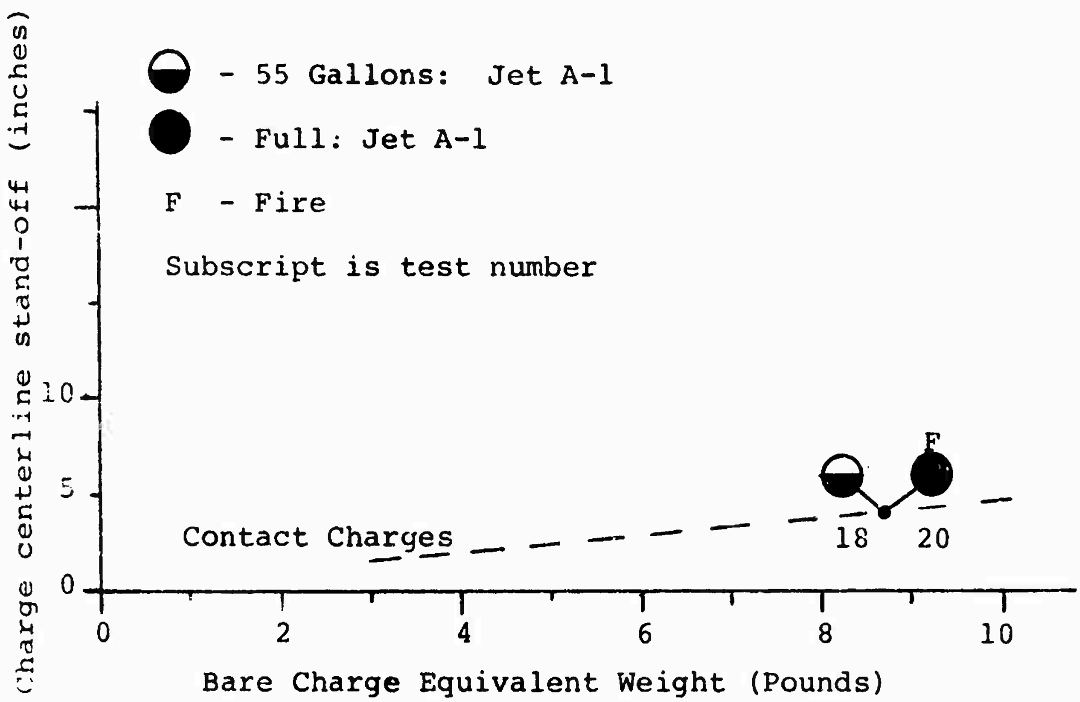

Figure 26. Midtank Vertical Position Test Results

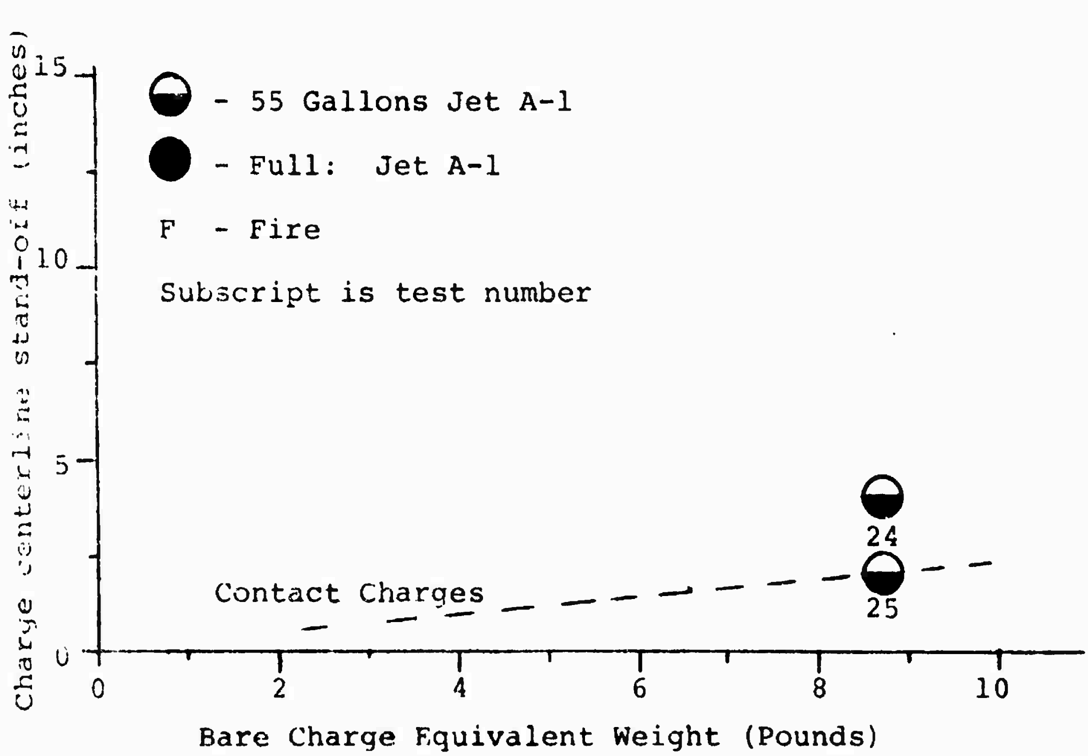

Figure 27. Midtank 45-Degree Position Test Results

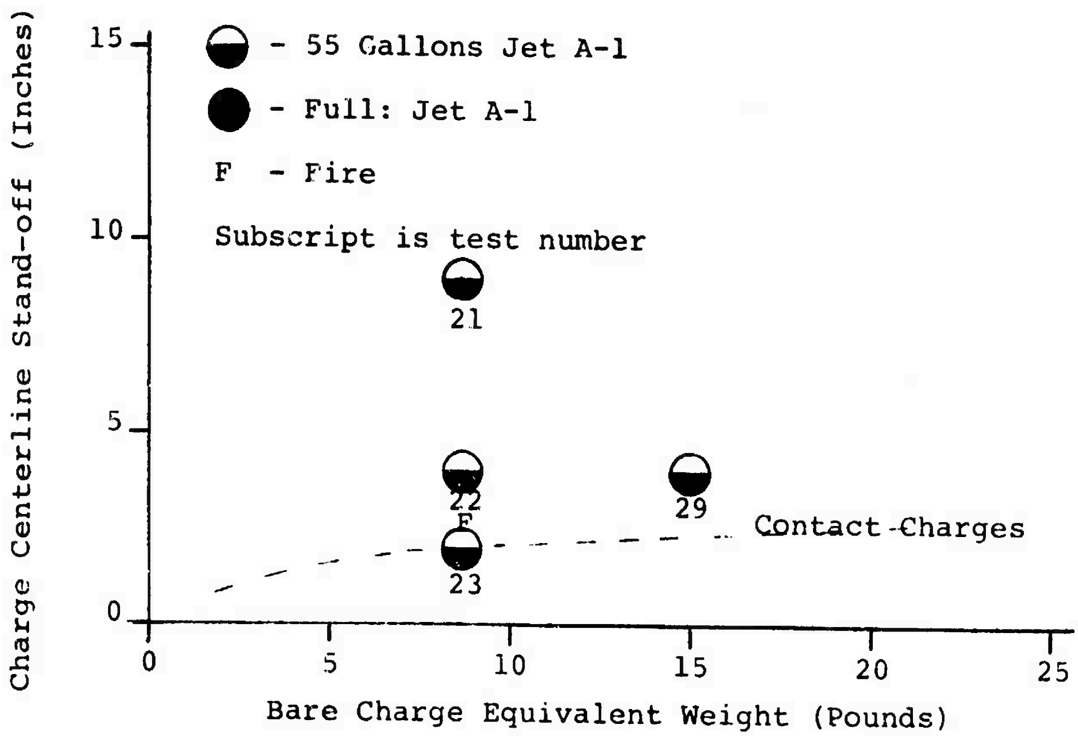

Figure 28. End Tank Horizontal Position Test Results

very low in other than the contact postiion. This is because, as the charge is moved away from the tank, the fireball is vented to the atmosphere almost immediately. Film analysis indicates that the fuel is forced down and out to the ends of the tank beneath the hot gases. By the time the fuel vapor has been thrown clear of the tank and crater, the hot gases have cooled too much for a flame front to occur. The full tank, however, instantaneously discharged the fuel, thus allowing immediate mixing and burning to occur.

3. Midtank 45-Degree

The two tests in the midtank 45-degree position (Figure 27) indicated that a slight standoff had a marginally better chance of starting a fire. This observation is based on the limited data in tests 24 and 25 in which a flash fire occurred in the 4-inch standoff position but not in the contact position. A possible reason for this was the retention of more fuel-soaked dirt alongside the tank, thus enhancing vapor ignition by hot particles. Whether the tank ends were uncovered or ruptured apparently had no effect on lethality.

4. End-Tank Horizontal

The results of the four tests in the end-tank horizontal position (Figure 28) again showed decreased lethality as compared to the midtank horizontal test results. Tank contact was necessary to initiate a fire when the 8.75-pound charge was used. The 15-pound charge, although only 4 inches away, did not start a fire even though the damage level was greater than for the smaller charge. Data analysis indicated that the charge location caused a shock wave to reflect off of the far end of the tank, ejecting a slug of liquid fuel which quenched the hot particles before the turbulence could disperse it into droplets. This fuel was distributed on the ground in line with the broken end of the tank. It is possible that a charge weight between 8.75 and 15 pounds might have a sufficient target damage level but not get the severe quenching effect, however, this was not further investigated.

D. TEST RESULTS

In this section each test is discussed individually. The parameters for a specific test can be found in Appendix A.

1. <u>Test No. 1</u>

This test, against a full tank, used 1.1 pounds of C-4 in the midtank horizontal test position. Stand-off distance was 4 inches.

Damage to the test tank consisted of localized tearing behind the end plate weld. The central portion of the tank was evenly crushed inward about 11 inches. Some of the fuel was ejected from the ruptures and had spread over the crater lip. No sustained fire was observed.

2. Test No. 2

This test against an empty tank used 1.1 pounds of C-4 in the midtank horizontal test position. Stand-off distance was 9 inches. Damage to the test tank was limited to crushing of the tank's central portion. The end plates were not ruptured. No ullage explosion or fire resulted.

3. Test No. 3

This test against a full tank used 8.75 pounds of C-4 in the midtank horizontal test position. Stand-off distance was 9 inches. A large and sustained fire was obtained with this test. The indication is that the fuel which was being ejected from the end plate tear area encountered the fireball from the explosive charge and caused ignition to occur. The end plates remained in a circular condition even though the cylindrical portion of the tank was completely collapsed with the windward side pushing against the leeward side. In addition to the deformation obtained within the tank, the tank itself was physically translated back and up and caused permanent damage in the tank directly behind the target tank (Tank C). This tank (Tank B) was permanently deformed, although not ruptured.

4. Test No. 4

This test against an empty tank used 8.75 pounds of C-4 in the midtank horizontal position. Stand-off distance was 23 inches. Damage to the test tank was limited to generalized crushing and translation. The backup tank was also partially crushed and translated about 7.5 inches. No ruptures of either tank occurred.

5. Test No. 5

This test was a repeat of Test No. 1 except that the 1.1-pound charge was encased in a steel housing to ascertain the effect of steel fragments being generated at the time of the explosion. As with Test No. 1, no fire resulted and the steel fragments were deflected or otherwise prevented from penetrating the tank skin. Hence, the same type of deformation and rupture occurred with this tank as with the one used in Test No. 1. Because of the casing effects, the crater was smaller than for Test No. 1.

6. <u>Test No. 6</u>

This test was a repeat of Test No. 2 except that the 1.1-pound charge was encased in a steel housing to ascertain the effect of steel fragments being generated at the time of the explosion. Damage to the tank consisted of general crushing of the central portion and tears 3 and 40 inches long, respectively, along each end plate.

7. <u>Test No. 7</u>

This test against a full tank used 8.75 pounds of C-4 in the midtank horizontal positon. Standoff distance was 17 inches. The test tank, besides sustaining general crushing in its central portion, was ruptured along both end plate welds. The fuel drained into the crater causing a large puddle (Figure 29), but no ignition occurred.

8. <u>Test No. 8</u>

This test was identical in configuration to Test No. 7 with the charge placed at a standoff distance of 13 inches. The general deformation of the tank was similar to that obtained in Test No. 7. However, in this case, a fuel fire was first observed along the crater lip. This fire propagated down the fuel stream draining from the tank until it had reached the fuel puddle in the crater. It is conceivable that the fire starting on the crater lip would not have, in all cases, propagated into the crater cavity and started the large sustained fire.

9. <u>Test No. 9</u>

This test against a half-full tank used 8.75 pounds of C-4 in the midtank horizontal position. Stand-off distance was 13 inches. One end plate was completely blown off of the test tank, which came to rest on top of the backup tank.

There was a small fire on the crater wall and over the rim. After 10 minutes of burning, puddled fuel in the crater had not ignited. In an attempt to extinguish the rim fire, flaming soil was accidentally knocked into the crater fuel puddle, thereby igniting the puddle. Since uncontrolled burning occurred and could have been generated by detonation, this test point is considered marginal with regard to fire-starting capability.

10. <u>Test No. 10</u>

This test against a half-full tank used 4.9 pounds of C-4 in the midtank horizontal position. Stand-off distance was 9

Figure 29. Typical Fuel Puddle in Crater

inches. Damage to the test tank was limited to generalized crushing of the central portion. Each end plate sustained small (<2-inch) ruptures near the weld lines. The 4.9-pound charge was chosen as it was the average of the 1.1- and 8.75-pound charges previously used.

11. Test No. 11

This test against a half-full tank used 4.9 pounds of C-4 in the midtank horizontal position. Stand-off distance was 4 inches. Damage to the test tank was extensive. The central portion nearest the charge was blown away, and the tank rotated on its long axis 60° away from the charge. The fuel spray covered a 60-foot-diameter circle behind the tank, but no ignition occurred.

12. Test No. 12

To ascertain if it was possible for a 4.9-pound charge to ignite a half-full tank, the 4.9-pound charge was placed in contact with the half-full tank at the midtank horizontal test position. Damage to the test tank was more severe than in Test No. 11, but no fuel ignition occurred even though the ground was thoroughly fuel soaked.

13. Test No. 13

As a check to see if there were any unique phenomena occurring with contact charges or near-field effects, an 8.75-pound charge was placed in contact with a half-full tank at the midtank horizontal test position. There was a large sustained fire confined mostly to the crater rim. The crater only had a small burning fuel puddle because most of the fuel had been blown away by the explosion.

14. Test No. 14

This test against a half-full tank used 8.75 pounds of C-4 in the midtank horizontal position. Standoff distance was 17 inches. This was a supplemental check to see if the fire obtained at the 13-inch stand-off was a marginal point. The test tank, besides sustaining general crushing of its central portion, had the fill pipe end mostly torn off. Most of the fuel was scattered about the crater, but there was no fire. From this, it was concluded that the 13-inch standoff using an 8.75-pound charge was the maximum standoff and minimum charge necessary for obtaining sustained fuel fires against the buried test tanks.

15. Test No. 15

This test against a half-full tank used 7 pounds of C-4 in the midtank horizontal test position. The charge was in contact with the tank. Damage to the tank was extensive with only the bottom portion unaffected by the explosion. All of the fuel was distributed outside of the crater, but no ignition occurred.

16. Test No. 16

This test against a half-full tank used 8 pounds of C-4 in the midtank horizontal test position. The charge was in contact with the tank. Besides doing extensive damage to the tank, the explosion threw the tank out of the crater. All of the fuel was distributed outside of the crater, but no ignition occurred.

17. Test No. 17

This test was a repeat of Test No. 16 except the charge was placed at a 4-inch stand-off. Test results were the same as Test No. 16, but the test tank was thrown farther out of the crater. There was no ignition of the spilled fuel.

18. Test No. 18

This test against a half-full tank used 8.75 pounds of C-4 in the midtank vertical test position. The charge was in contact with the tank. The top central portion of the test tank was blown through the bottom of the tank. A puddle of fuel remained in the tank, but no ignition occurred.

19. Test No. 19

Test No. 19 was an exceptional test in that, rather than using one of the standard test tanks, a commercial 55-gallon steel drum was half-filled with fuel and laid on its side on the surface. One and one-half pounds of C-4 was taped to the side of the tank in the midtank horizontal test position. The purpose of this test was to demonstrate that a small charge could ignite the fuel spray when the test tank was uncovered.

At detonation, a violent fire occurred and continued until all fuel was consumed. This test illustrated the large quenching effect the dirt had on the buried tank tests. It appeared that the soil provided a buffer between the detonation products and the escaping vapors so that the interaction of the hot detonation products and the fuel vapors never occurred and thus did not ignite the vapors. Second, in those cases where ignition did occur, the soil which had been thrown up and fell back to the earth provided a fine mist which extinguished the fire much as the fire-fighting technique of applying a light water spray over a flame area and starving the vapors so that they cannot burn. Some of the burning fuel was also thrown into one of the craters that had been made from a previous test and ignited the fuel-saturated ground in the crater. This indicates that there may be a need for considering synergistic effects in establishing fire-starting capabilities against underground POL storage tanks.

20. Test No. 20

This test against a full tank used 8.75 pounds of C-4 in the midtank vertical test position. The charge was in contact with the tank. The top of the test tank and both end plates were blown away. At detonation a large fireball rose about 40 feet. As the fireball dissipated, the falling liquid fuel caught fire giving the appearance of a red water fall. The fire in the crater consumed all the fuel and lasted for approximately 30 minutes. Hence, the threshold charge was capable of starting a fire when detonated on top of a full tank, but failed to start a fire when detonated on top of a half-full tank.

21. Test No. 21

This test against a half-full tank used 8.75 pounds of C-4 in the end tank horizontal test positon. Stand-off distance was 9 inches. The purpose of this test was to ascertain a lethal stand-off distance from the end of the tank with regard to fire-starting capability. The end plate of the tank closest to the charge was sheared off. The tank was pinched closed over about two feet of its length and elevated to around 30 degrees off the horizontal. The end of the tank furthest from the charge was undamaged and was capable of holding approximately 25 gallons of fuel. A short duration fireball, approximately one to two seconds, existed. However, no sustained fire was obtained. No fuel puddle was found in the crater since the fuel that was not sprayed out remained in the tank.

22. Test No. 22

This test against a half-full tank used 8.75 pounds of C-4 in the end tank horizontal test position. Stand-off distance was 4 inches. The end plate nearest the charge was sheared off. The top seam of the tank was peeled back inside the tank for three to four feet. Five gallons of fuel remained in the tank. Additional fuel was puddled in the crater. The end of the tank furthest from the charge remained covered. There was no smoke or fire observed.

23. Test No. 23

This test against a half-full tank used 8.75 pounds of C-4 in the end tank horizontal test position. The charge was in contact with the tank. At detonation a sustained fire lasting about 10 minutes occurred. The end plate nearest the charge was sheared off and thrown 30 feet behind the fuel tank. The tank was crimped in on itself, leaving the far end undamaged and still covered with soil. There was no fuel left in the tank or crater.

24. Test No. 24

This test against a half-full tank used 8.75 pounds of C-4 in the midtank 45-degree test position. Stand-off distance was 4 inches. The central top portion of the tank was blown in on itself. Both end plates were sheared off, but the ends of the tank remained covered with soil. A fuel puddle of about 10 gallons remained in the tank. A vapor fire of 1 to 2 seconds duration occurred, but there was no sustained ground fire.

25. Test No. 25

This test against a half-full tank used 8.75 pounds of C-4 in the midtank 45-degree test position. The charge was in contact with the tank. The blast opened the tank into a trough shape with both ends sheared off and partially uncovered. About 20 gallons of fuel remained in the tank. No vapor or sustained fire occurred.

26. Test No. 26

This test against a half-full tank used 15 pounds of C-4 in the midtank horizontal test position. Stand-off distance was 16 inches. The blast threw the fuel tank over the back-up tank a distance of 30 feet. The tank was crushed with the end nearest the filler pipe torn off. The other end was torn for 300 degrees. The backup tank was lifted out of the crater and turned perpendicular to its original position. No fire was observed.

27. Test No. 27

This test against a half-full tank used 15 pounds of C-4 in the midtank horizontal test position. Stand-off distance was 13 inches. The test tank was thrown out of the crater over the back-up tank, a distance of 30 feet.

A large sustained fire surrounded the test tank, but there was no fuel or fire in the crater. The tank was totally crushed, both ends were sheared off, and the center had a vertical tear from top to bottom.

28. Test No. 28

This test against a half-full tank used 30 pounds of C-4 in the midtank horizontal test position. The stand-off distance was 16 inches. The test tank was thrown from the crater exactly as in Test No. 27, but in this case both end plates remained in the crater. The backup tank was crushed down to one-half of its original diameter and lifted 10 inches off its base. There was a sustained fire immediately around the test tank but no fuel or fire in the crater area.

29. Test No. 29

This test against a half-full tank used 15 pounds of C-4 in the end tank horizontal test position. The stand-off distance was 4 inches. The blast sheared off the near end of the fuel tank, split the top for a distance of 3 feet, and lifted the far end of the tank about 2 feet. No fuel remained in the tank or crater. There was no smoke or fire.

30. Test No. 30

This test against a half-full tank used 30 pounds of C-4 in the midtank horizontal test position. The stand-off distance was 24 inches. The tank was flattened over its whole length and thrown 3 feet behind the rear crater lip. Both end plates remained in the crater. There was no fire or residual fuel puddle.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The objective of this program was to generate basic test data that can be used to evaluate the lethality of inventory and developmental warheads against typical underground petroleum/oil/lubricant (POL) storage facilities. The program was phased toward accomplishing the above objective. In order to investigate and define tank rupture contours and compare them with those generated from larger scale models, representative one-third scale model POL storage facilities were constructed for testing. The POL targets were subjected to shock damage using various sizes and configurations of buried explosive charges against tanks both filled and partially filled with jet fuel.

Studies of ignition and propagation mechanisms were initiated next. This phase involved experimental and analytical research necessary to develop relations establishing ignition criteria for the jet fuel by detonating explosive gases.

The combined results of both phases provided a data base for fuel ignition by an underground detonation. The data is sufficient to assess the ignition effectiveness of underground detonations against POL targets.

A. CONCLUSIONS

Based on review of all the data, several conclusions were drawn. These conclusions are given with supporting rationale.

1. Conclusion - Large munitions are required to start sustained fires when attacking the tested underground POL tanks. The bare charge equivalent weight should be in excess of 235 pounds of Composition C-4 explosive.

Rationale - Twenty-nine sub-surface tests and one above-surface test were conducted. Compositon C-4 explosive charge weights ranged from 1.1 to 30 pounds. Since these tests were considered one-third scale, full scale bare charge weights of 30 pounds to 810 pounds were evaluated.

A minimum threshold value of 8.75 pounds (full scale-236 pounds) of explosive was established for achieving sustained fire. Tests with 8.0 pounds (full scale-216 pounds) charges did not produce fires. Further, the threshold value of 8.75 pounds was sufficient only for certain charge positions relative to the target tank periphery.

2. Conclusion - Fuze settings should be made to provide the largest crater possible.

Rationale - As the charge (constant weight) was moved closer to the end of the tank or to a higher elevation, the distance between the charge and tank had to be decreased to obtain a sustained fire. The threshold charge started sustained fires at a 13-inch standoff when detonated in the midtank horizontal test position. This charge had to be placed in contact with the tank to obtain a sustained fire when detonated in the end tank horizontal test position. A sustained fire was obtained against a full tank but not a half-full tank when the 8.75-pound threshold charge was detonated in the midtank vertical test position.

From the data it was found that for a sustained fire to occur:

a. Both ends of the fuel tank had to be uncovered.

b. Both ends of the fuel tank had to be ruptured and/or separated.

c. The crater had to be at least 48 inches deep.

When these conditions existed, enough fuel vapor was ignited by the hot detonation products so that a sustained fire was generated. The soil fall-out was then insufficient to smother the fire.

3. Conclusion - For any weapon to start a fire, the target tank must be within the crater and (a) have both ends of the tank ruptured sufficiently to produce a fuel spray, or (b) have the tank translated sufficiently so that fuel dispersion occurs as the tank translates and ruptures.

Rationale - The smaller charges (8.75 pounds) tended to rupture tank ends so a fuel vapor was generated which then ignited as the vapor interacted with the detonation products. The larger charges produced the same type of tank structure collapse plus a larger degree of tank translation. For a sustained fire to start in either case, the vapors had to be ignited and they, in turn, supplied the heat necessary to ignite any fuel puddle. For the smaller charges this puddle was in and about the crater, while for the larger charges it existed around the fuel tank which was blown out of the crater. Hence, as the tank was deformed and/or translated, it had to disperse the fuel so vapors could be ignited and, in turn, provide the ignition source for the puddled fuel.

B. RECOMMENDATIONS

As a result of the data generated in this program, several recommendations are set forth:

1. Recommendation - Review the methods of piping and pumping fuel from the storage containers to other points and conduct a series of tests to establish the effect of pipe rupture and fuel spillage on the probability of fuel ignition from these sources in conjunction with underground detonations.

Rationale - Deformation and translation of the fuel tanks will cause piping and junctures to break. This will provide sources of fuel vapors and/or cause puddling. In the former case, rupturing of the tank ends may not be required if venting and ignition of fuel vapors through piping damage can be achieved. In the latter case, puddling of the fuel provides another place for a sustained fire to ignite.

2. Recommendation - Review the tie-down techniques for the fuel tanks and conduct tests to establish the effect of container restraints on tank ejection from the crater area and subsequent fire ignition.

Rationale - It is known that, as underground fuel tanks are drained, the hydrostatic pressure of the surrounding ground water tends to lift the empty tank out of the ground. To eliminate this, underground tanks are restrained by buried cables passed over their top surfaces and anchored remotely from the tank. It is possible that tie-down cables could tear the tanks as they are translated by the detonated charge. This would result in additional venting of the fuel and, possibly, easier ignition of the fuel vapors. Secondly, if the tanks are restrained to the crater area, puddling and burning would be generally confined to the crater area. The soil fall-out problem could be severe in such a case. Whether the tearing possibility or tank restraint possibility dominates, and the effect of each, should be investigated and defined.

3. Recommendation - A series of tests should be conducted to establish synergistic effects such as when one warhead ruptures a tank without igniting a sustained fire and a second warhead provides the source for subsequent ignition of the spilled fuel.

Rationale - During the single above-ground test, burning fuel from the exploded tank ignited fuel in a nearby crater. This result demonstrated that it was possible to puddle fuel in craters using a charge weighing less than the threshold value and ignite the fuel-soaked earth a day later with the burning particles generated by another charge. This suggests that mixed loads of weapons could be employed to expose and then ignite fuel. However, further testing and analysis are required before conclusive recommendations can be made for such a tactical approach.

4. Recommendation - A detailed theoretical and experimental

investigation into dynamic scaling effects in fire ignition and propagation should be conducted.

<u>Rationale</u> - Fire phenomena can be modeled by using high pressure techniques. However, the similitude laws developed for this fluid dynamics mechanics are different from those of shock wave fluid mechanics. The chief factor is that of gravity which is considered in fire modeling and neglected in shock wave modeling. Hence, when both phenomena are considered, different similitude models must be applied to different time phases of the event. It is highly desirable to establish a single set of model laws applicable throughout the entire event sequence.

5. <u>Recommendation</u> - The effects of incorporating incendiary material into munitions with regard to dispersing these incendiary particles and causing fires to start in fuel-filled craters should be investigated.

<u>Rationale</u> - Fuel spillage due to tank rupture is quite prevalent in target attacks. Further, fuel vapors generated by the rupturing tanks expand over large regions in comparison to the hot detonation products. Hence, work should be done to better define the ignition capabilities of hot, short lapse time incendiary particles as well as the longer burning hot particles capable of igniting puddled fuel.

APPENDIX A

TEST DATA SHEETS

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This appendix contains basic field test data for each of the 30 experiments. Also, two photographs are presented to show fuel tank damage, crater characteristics, and general after-detonation results for all tests.

TEST DATA SHEET

Test 1 Date 6-28-74 Ambient 85°F
Fuel Jet A-1 Wind Calm Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 1.1 Standoff (Inches) 4 Location Mid-Tank Horizontal
Length (Inches) 6 Diameter (Inches) 2 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: Full = 124 Gallons Test Tank A
Tank A Full Tank C Full
Tank B Empty Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 72 Inches
Length Parallel to tank 96 Inches
Depth 27 Inches

Fire No Characteristics:

Test Results:

The central portion of the test tank directly in front of the charge was pushed in 12 inches. The left end plate weld was torn for a distance of 53 inches. The right end plate weld was torn for a distance of 46 inches. The longitudinal tank weld was not torn. Fuel was sprayed over a large area with little fuel left in the tank.

The base of the concrete sump between Tanks A and B was cracked. Both side slabs were rotated 90° in a horizontal plane and came to rest on top of the other sump.

Other Data:

The tanks used were made of M1020 steel 0.125 thick by 66 inches long by 24 inches in diameter. A four-tank array with concrete valve assembly covers was used. One gallon of fuel was used in each empty tank for Tests 1 through 30.

Soil Mechanics Data:

Sample Volume	4.67	Cubic Inches			
Wet Weight	0.287	Pound	Wet Density	106.1	Pounds/Ft^3
Dry Weight	0.266	Pound	Dry Density	98.6	Pounds/Ft^3
Moisture	7.3%	by Weight			

Figure A-1. Post-Test Closeup of Fuel Tank From Test No. 1

Figure A-2. Overview of Test Site Damage for Test No.1

TEST DATA SHEET

Test 2 | Date 7-1-74 | Ambient 90° F
Fuel Jet A-1 | Wind Calm | Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 1.1 Standoff (Inches) 9 Location Mid-Tank Horizontal
Length (Inches) 6 Diameter (Inches) 2 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: Full = 124 Gallons Test Tank B
Tank A Full Tank C Full
Tank B Empty Tank D Empty

Target Damage Slight

Crater Data: Length Perpendicular to tank 65 Inches
Length Parallel to tank 78 Inches
Depth 30 Inches

Fire No Characteristics:

Test Results:

The test tank was not ruptured. The concrete assembly between Tanks A and B was translated eight inches away from the charge. The test tank was crushed in along its whole side.

Degrees from Horizontal	*Longitudinal Location (Inches)						
	Fill Pipe End						
	+18	+12	+6	Centerline	-6	-12	-18
+60	0	0	1	2	2¼		1½
+30	4¼	5½	6½	7½	7 3/4	7½	7¼
Horizontal	6 3/4	8¼	10	11	11	10¼	9¼
-30	4	6	7	8	8	8	7½
-60	½	1¼	2	2½	3½	2½	2

*Deviation from Circle

Other Data:
This data was the same as Test No. 1.

Figure A-3. In Situ Post-Test Closeup of Fuel Tank From Test No. 2

Figure A-4. Closeup of Crater and Tank Damage for Test No. 2

TEST DATA SHEET

Test 3 Date 7-2-74 Ambient 90°F
Fuel Jet A-1 Wind Calm Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 9 Location Mid-Tank Horizontal
Length (Inches) 12 Diameter (Inches) 8.75 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: Full = 124 Gallons Test Tank C
Tank A Full Tank C Full
Tank B Empty Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 168 Inches
Length Parallel to tank 168 Inches
Depth 54 Inches

Fire Yes Characteristics:

The detonation spread flaming fuel over a large area. The fire was extremely violent and hot, lasting in excess of an hour.

Test Results:

The test tank was crushed flat. Both end plates were severed from the tank. The test tank was pushed into the backup tank causing minor damage to the backup tank. The concrete valve assembly cover nearest to the charge was torn apart by the blast. Both sides were thrown a distance of 60 feet. The end piece was thrown 125 feet. The base piece remained near the tanks.

Other data:

This data was the same as Test No. 1.

Figure A-5. Post-Test Closeup of Target
Array for Test No. 3

Figure A-6. Overview of Crater Fire and
Tank Damage From Test No. 3

TEST DATA SHEET

Test 4 | Date 7-2-74 | Ambient 90°F
Fuel Jet A-1 | Wind Calm | Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 22 | Location Mid-Tank Horizontal
Length (Inches) 12 Diameter (Inches) 4 | Type C-4

Film Coverage: HYCAM @ 3100 PPS Lens 25 MM @ f [illegible].6

Fuel Level: Full + 124 Gallons | Test Tank D
Tank A Full | Tank C Full
Tank B Empty | Tank D Empty

Target Damage Slight

Crater Data: Length Perpendicular to tank 180 Inches
Length Parallel to tank 150 Inches
Depth 48 Inches

Fire No Characteristics:

Test Results:

The test tank was partially crushed and pushed into the backup tank. That tank was moved 7½ inches rearward. Neither tank was ruptured. The concrete valve assembly cover nearest to the charge was thrown 12 feet behind the tank array. The valve assembly cover farthest from the charge was lifted and rotated 90 in the horizontal plane.

Degrees from Horizontal	* Longitudinal Location (Inches)					
	Fill Pipe End +18 12	6	Center	-6	-12	-18
+60	Extensive	11	11 3/8	10 1/2	10 1/8	0
+30	Flattening	13 7/8	13 1/8	12 3/4	12	11 1/4
Horizontal	Fill Pipe	14 1/8	13 1/4	12 3/4	12	11 5/8
-30	Pushed in	12 5/8	11 1/2	11 1/4	10 1/2	1 1/2
-60	14 Inches	10 1/8	0	0	0	0

* Deviation from Circle

Other Data:

This data was the same as Test No. 1.

Figure A-7. Overview of Crater and Tank Damage For Test No. 4

TEST DATA SHEET

Test 5 Date 7-15-74 Ambient 85°F
Fuel Jet A-1 Wind Calm Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 1.1* Standoff (Inches) 4 Location Mid-Tank Horizontal
Length (Inches) 6 Diameter (Inches) 2 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: Full = 124 Gallons Test Tank A
Tank A Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Slight

Crater Data: Length Perpendicular to tank 57 Inches
Length Parallel to tank 70 Inches
Depth (Crater was partially refilled) 17 Inches

Fire No Characteristics:

Test Results:

The explosion pushed in the central portion of the test tank. No fractures or fuel leakage occurred.

Degrees from Horizontal	*Longitudinal Location (Inches)							
	Fill Pipe End							
	24	+18	12	6	Center	-6	-12	-18
60	0	2	1	0	0	0	0	0
30	0	1 1/2	3 1/4	6 3/4	5 1/2	3 1/2	2	0
0	0	2 1/2	7 1/4	9 3/4	9 1/4	7 1/2	5	1 3/4
-30	4	8	9 3/4	10 1/2	10 1/2	9 1/4	7	3 1/4
-60	0	3	4 1/2	4 1/2	4 1/2	3 1/4	2	0
-90	0	0	0	1	3	1	0	0

* Deviation from Circle

Other Data:

A two-tank array was used with one tank behind the other. No concrete covers were used in this test or in Tests 6 through 30. Unless otherwise noted, the two-tank array was used for all subsequent tests.

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* This test had the explosive encased in a steel pipe to test for fragmentation effects. The pipe had an outside diameter of 2.375 inches, a wall thickness of 0.154 inch and weighed 1.83 pounds. This was equivalent to a bare charge explosive weight of 0.424 pound.

Figure A-8. Closeup of Damaged Fuel Tank From Test No. 5

TEST DATA SHEET

Test 6 | Date 7-15-74 | Ambient 85° F
Fuel Jet A-1 | Wind Calm | Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 1.1* Standoff (Inches) 9 Location Mid-Tank Horizontal
Length (Inches) 6 Diameter (Inches) 2 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ ƒ 5.6

Fuel Level: Full = 124 Gallons Test Tank D
Tank A Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 48 Inches
Length Parallel to tank 72 Inches
Depth (Crater was partially refilled) 16 Inches

Fire No Characteristics:

Test Results:

The explosion deeply dented the central portion of the test tank. The end nearest the fill pipe sustained a 3-inch long tear while the opposite end of the tank was torn 40 inches along the end plate weld.

Degrees from Horizontal	* Longitudinal Location (Inches)								
	Fill Pipe End								
	+18	+12	+6	Center	-6	-12	-18	-24	-33
60	0	0	0	4	4 1/2	4	2 3/4	1/2	3
30	2	4 1/2	6 1/2	9 1/2	11 1/2	11 1/2	11 1/2	9 1/2	3
0	2 3/4	5 1/4	7 3/4	9 1/2	11	12	12	10	3
30	2	3 1/4	5 1/2	9 3/4	11 1/4	12 3/4	11 1/2	9 1/2	3
60	1/2	2	4 1/2	5 1/4	7 1/2	8	6 1/2	3	0

* Deviation from Circle

Other Data:

This data was the same as Test No. 5

Soil Mechanics Data:

Sample Volume: 4.67 cubic inches
Net Weight 0.306 Pound Wet Density 113.6 Pounds/Ft^3
Dry Weight 0.286 Pound Dry Density 106.1 Pounds/Ft^3
Moisture 6.6% By Weight

---

* This test had a cased charge exactly like Test No. 5.

Figure A-9. Closeup of Damaged Fuel Tank From Test No. 6

TEST DATA SHEET

Test 7 | Date 7-18-74 | Ambient 85°F
Fuel Jet A-1 | Wind Calm | Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 17 Location Mid-Tank Horizontal
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 4.0

Fuel Level: Full = 124 Gallons | Test Tank A
Tank A Full | Tank C Not used
Tank B Not used | Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 144 Inches
Length Parallel to tank 132 Inches
Depth 54 Inches

Fire No Characteristics:

Test Results:

The explosion fractured the fill pipe closest to it. The tank was split behind the end plate weld for a distance of 200°. The fill pipe end of the tank was also split behind the end plate weld. Most of the fuel drained into the crater causing a large fuel puddle.

Other Data:

This data was the same as Test No. 5.

Figure A-10. Closeup of Damaged Fuel Tank From Test No. 7

Figure A-11. Overview of Crater and Tank Damage
for Test No. 7

TEST DATA SHEET

Test 8 — Date 7-18-74 — Ambient 85° F

Fuel Jet A-1 — Wind Calm — Sky Clear, Sun

Explosive Charge:

Weight (Pounds) 8.75 Standoff (Inches) 13 Location Mid-Tank Horizontal

Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 4.0

Fuel Level: Full = 100 Gallons — Test Tank A

Tank A Full — Tank C Not used

Tank B Not used — Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 156 Inches

Length Parallel to tank 132 Inches

Depth 54 Inches

Fire Yes Characteristics:

The fire was located initially on the crater wall, then spread to the fuel puddle after one minute. After three minutes the fire was uncontrollable. All of the fuel was consumed.

Test Results:

This test established the standoff distance required for a sustained fire. The end plate nearest to the fill pipe was sheared off. The body of the tank had a tear 18 inches long and parallel to the end plate and 12 inches from the end. The fuel formed a large puddle in the crater.

Other Data:

This data was the same as Test No. 5.

Figure A-12. In Situ Closeup of Damaged Fuel Tank
From Test No. 8

Figure A-13. Overview of Crater Fire and Tank Damage
For Test No. 8

TEST DATA SHEET

Test 9 Date 7-26-74 Ambient 90-95°F
Fuel Jet A-1 Wind 0-3 MPH Sky Partially Cloudy

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 13 Location Mid-Tank Horizontal
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 1.4

Fuel Level: 1/2 Full = 55 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 174 Inches
Length Parallel to tank 150 Inches
Depth 54 Inches

Fire Yes Characteristics:

The fire was located on the upper crater wall to the left of the tank. After 10 minutes it had not spread to the fuel puddle in the crater.

Test Results:

The test tank was crushed to a thickness of eight inches. It was thrown upward and backward coming to rest on top of the backup tank. The left end plate was sheared off, while the right end plate was 3/4 separated. There was a fuel puddle in the crater. The fuel was also sprayed over the ground behind the crater.

Other Data:

This data was the same as for Test No. 5.

Figure A-14. Closeup of Damaged Fuel Tank From Test No. 9

Figure A-15. Crater and Tank Damage for Test No. 9

TEST DATA SHEET

Test 10 Date 8-2-74 Ambient °F
Fuel Jet A-1 Wind ____ Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 4.9 Standoff (Inches) 9 Location Mid-Tank Horizontal
Length (Inches) 9.9 Diameter (Inches) 3.3 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 55 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Slight

Crater Data: Length Perpendicular to tank 126 Inches
Length Parallel to tank 126 Inches
Depth 44 Inches

Fire No Characteristics:

Test Results:

The test tank was torn behind both end plates; one inch on the fill pipe end and two inches on the other end. The central portion of the tank was pushed in 12 inches, tapering to four inches at the tank ends. The ends of the tank remained buried.

Other Data:

The test tank was identical with previous tanks except that a single 1 1/2-inch -diameter filler pipe was used. It was positioned on the longitudinal weld seam. This single fill pipe configuration was used on Tests No. 10 through No. 30 unless otherwise noted.

Figure A-16. Closeup of Damaged Fuel Tank From Test No. 10

Figure A-17. Overview of Crater and Fuel Spray Pattern for Test No. 10

TEST DATA SHEET

Test 11 Date 8-6-74 Ambient °F
Fuel Jet A-1 Wind ______ Sky Overcast

Explosive Charge:
Weight (Pounds) 4.9 Standoff (Inches) 4 Location Mid-Tank Horizontal
Length (Inches) 9.9 Diameter (Inches) 3.3 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 4.0

Fuel Level: 1/2 Full = 55 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 99 Inches
Length Parallel to tank 106 Inches
Depth 40 Inches

Fire No Characteristics:

Test Results:

The explosion made a hole in the side of the tank 4 1/2 feet long and 2 feet wide. The tank rotated 60° about its longitudinal axis away from the explosion. A fine mist of fuel covered a large area of ground. Several steel fragments penetrated the rear portion of the tank. Neither end of the tank was ruptured although some weld area necking did occur.

Other Data:

This data was the same as for Test No. 10.

Soil Mechanics Data:

Sample Volume 4.67 Inches
Net Weight 0.265 Pound
Dry Weight 0.251 Pound
Moisture 5.3% By Weight

Wet Density 98.05 Pounds/Ft^3
Dry Density 93.0 Pounds/Ft^3

Figure A-18. Closeup of Damaged Fuel Tank in Crater From Test No. 11

Figure A-19. Overview of Crater and Fuel Tank For Test No. 11

TEST DATA SHEET

Test 12 Date 8-6-74 Ambient °F
Fuel Jet A-1 Wind ______ Sky Overcast

Explosive Charge:
Weight (Pounds) 4.9 Standoff (Inches) 1.65 Location Mid-Tank Horizontal
Length (Inches) 9.9 Diameter (Inches) 3.3 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 4.0

Fuel Level: 1/2 Full = 55 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 87 Inches
Length Parallel to tank 96 Inches
Depth 36 Inches

Fire No Characteristics:

Test Results:

The explosion rotated the tank 45° about its longitudinal axis. The tank was pushed up out of the ground so that it came to rest 30° off the vertical. The side of the tank was blown away with large perforations also on the far side. The left end plate was 95 percent sheared off. All of the fuel was blown out of the tank in a 60-foot-diameter circle. No fuel remained in the crater.

Other Data:

This data was the same as for Test No. 10.

Soil Mechanics Data.

Sample Volume 4.67 In.
Wet Weight 0.273 Pound Wet Density 101 Pounds/Ft^3
Dry Weight 0.260 Pound Dry Density 96.1 Pounds/Ft^3
Moisture 4.7% By Weight

Figure A-20. Closeup of Tank in Crater
From Test No. 12

gure A-21. Overview of Crater and Damaged Fuel Tank
From Test No. 12

TEST DATA SHEET

Test 13 | Date 8-8-74 | Ambient 75°F
Fuel Jet A-1 | Wind Calm | Sky Partial Cloud Cover

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 2 | Location Mid-Tank Horizontal
Length (Inches) 12 Diameter (Inches) 4 | Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 55 Gallons | Test Tank A
Tank A 1/2 Full | Tank C Not used
Tank B Not used | Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 126 Inches
Length Parallel to tank 132 Inches
Depth 48 Inches

Fire Yes Characteristics:

There was a large (30 to 40 feet diameter) fireball at detonation. The ground fire was located on the crater rim behind the tank. There was no fuel puddle.

Test Results:

The tank was rotated 90° about its longitudinal axis and pushed partially up onto the backup tank. The side of the tank facing the explosive was blown away while the rear surface sustained multiple punctures. There was no fuel puddle in the crater.

Other Data:

This data was the same as Test No. 10.

Figure 22. Closeup of Damaged Fuel Tank in Crater
From Test No. 13

Figure A-23. Overview of Crater Fire and Damaged Fuel Tank
From Test No. 13

TEST DATA SHEET

Test 14   Date 8-9-74   Ambient 75°F
Fuel Jet A-1   Wind Calm   Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 17   Location Mid-Tank Horizontal
Length (Inches) 12 Diameter (Inches) 4   Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 55 Gallons   Test Tank A
Tank A 1/2 Full   Tank C Not used
Tank B Not used   Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 132 Inches
Length Parallel to tank 140 Inches
Depth 48 Inches

Fire No Characteristics:

Test Results:

The central portion of the tank facing the explosive was pushed in 6 to 9 inches. The left end plate was sheared off of the tank but the right end of the tank remained buried. The fuel was spread evenly over the ground with about 5 gallons puddled in the crater.

Other Data:

This data was the same as Test No. 10.

Figure A-24. Closeup of Damaged Fuel Tank
From Test No. 14

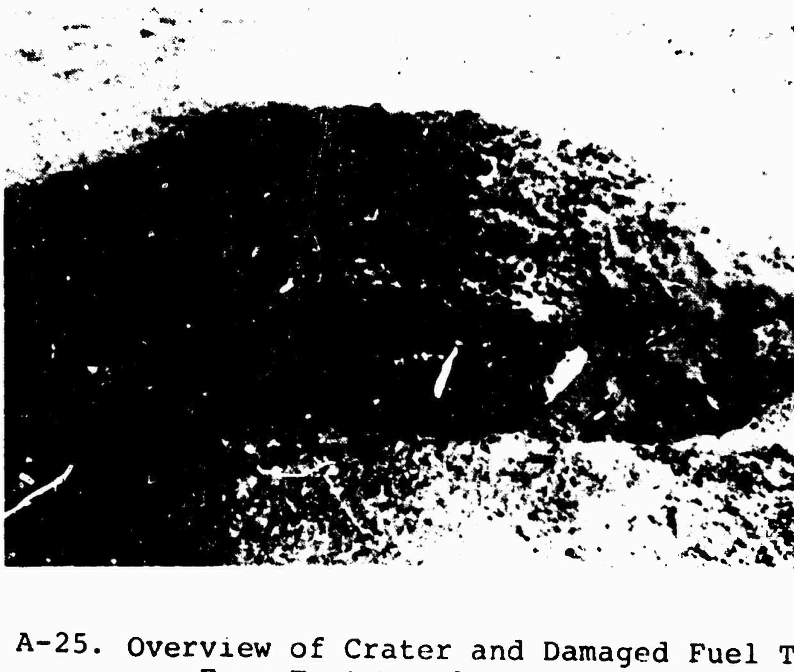

Figure A-25. Overview of Crater and Damaged Fuel Tank
From Test No. 14

TEST DATA SHEET

Test 15 Date 8-22-74 Ambient °F

Fuel Jet A-1 Wind ______ Sky Clear, Sun

Explosive Charge:

Weight (Pounds) 7.0 Standoff (Inches) 1.86 Location Mid-Tank Horizontal

Length (Inches) 11.16 Diameter (Inches) 3.72 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A

Tank A 1/2 Full Tank C Not used

Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 132 Inches

Length Parallel to tank 126 Inches

Depth 48 Inches

Fire No Characteristics:

Test Results:

Both ends of the tank were severed from the cylindrical portion. The cylindrical portion was partially blown away and translated into the backup tank. The fuel covered a 40-foot-diameter circle with no fuel remaining in the tank or crater.

Other Data:

The test tank was 60 inches long by 24 inches in diameter. This length tank was used for Tests No. 15 through No. 30 unless otherwise noted.

Figure A-26. Closeup of Damaged Fuel Tank From Test No. 15

Figure A-27. Overview of Crater and Damaged Fuel Tank From Test No. 15

TEST DATA SHEET

Test 16 Date 8-22-74 Ambient °F
Fuel Jet A-1 Wind ______ Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.0 Standoff (Inches) 1.94 Location Mid-Tank Horizontal
Length (Inches) 11.6 Diameter (Inches) 3.88 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 144 Inches
Length Parallel to tank 132 Inches
Depth 42 Inches

Fire No Characteristics: A cloud of white smoke was seen immediately after detonation.

Test Results:

The blast blew the tank completely out of the ground. The fill pipe end of the tank was severed while the other end was 50 percent severed. The central portion of the tank was blown away. The fuel spray covered an elliptical area 60 feet by 40 feet. No fuel remained in the crater.

Other Data:

This data was the same as Test No. 15.

Figure A-28. Closeup of Damaged Fuel Tank
From Test No. 16

Figure A-29. Overview of Crater and Damaged Fuel Tank
From Test No. 16

TEST DATA SHEET

Test 17 Date 8-22-74 Ambient 90° F
el Jet A-1 Wind 0-5 MPH Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.0 Standoff (Inches) 4 Location Mid-Tank Horizontal
Length (Inches) 11.6 Diameter (Inches) 3.88 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 132 Inches
Length Parallel to tank 144 Inches
Depth 48 Inches

Fire No Characteristics:

Test Results:

The explosion blew the cylindrical portion of the tank out of the crater but left both end plates in the crater. The tank was about 20 feet behind the crater center. The fuel was spread between the tank and rear crater wall.

Other Data:

This data was the same as Test No. 15.

Figure A-30. Closeup of Damaged Fuel Tank From Test No. 17

Figure A-31. Overview of Crater and Damaged Tanks from Test No. 17

TEST DATA SHEET

Test 18 | Date 8-23-74 | Ambient °F
Fuel Jet A-1 | Wind | Sky Cloudy

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 2 Location Mid-Tank Vertical
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 4.0

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank ______ Inches
Length Parallel to tank ______ Inches
Depth ______ Inches

Fire No Characteristics:

Test Results:

The explosion blew away the upper central portion of the tank. Both end plates were partially severed from the upper portion of the tank. About 20 gallons of fuel was left in the tank.

Other Data:

This data was the same as Test No. 15.

Figure A-32. Closeup of Damaged Fuel Tank From Test No. 18

Figure A-33. Closeup of Damaged Fuel Tank
In Crater From Test No. 18

TEST DATA SHEET

Test 19 | Date 8-23-74 | Ambient 85°F
Fuel Jet A-1 | Wind Calm | Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 1 1/4 Standoff (Inches) * Location Mid-Tank Horizontal
Length (Inches) ____ Diameter (Inches) ____ Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f5.6

Fuel Level: 30 Gallons of Fuel Test Tank *55-Gallon Steel Drum
Tank A Not used Tank C Not used
Tank B Not used Tank D Not used

Target Damage Heavy

Crater Data: (Tank above ground, no crater.)
Length Perpendicular to tank ____ Inches
Length Parallel to tank ____ Inches
Depth ____ Inches

Fire Yes Characteristics:

There was a 50-foot fireball lasting 2 seconds. A secondary fire was started in an old test crater about 30 feet from the drum.

Test Results:

The blast totally destroyed the fuel drum. A piece of steel 1 1/2 feet square was thrown about 400 feet.

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*Other Data:

In this test a standard 55-gallon steel (16 gauge wall) drum was used instead of the larger fuel tank. The drum was laid on its side on the ground. A standard 1 1/4-pound block of C-4 explosive was attached to the outside of the drum at the fuel-free surface with tape. The longitudinal weld on the drum was located 180° from the charge.

Figure A-34. Closeup of Damaged Fuel Tank From Test No. 19

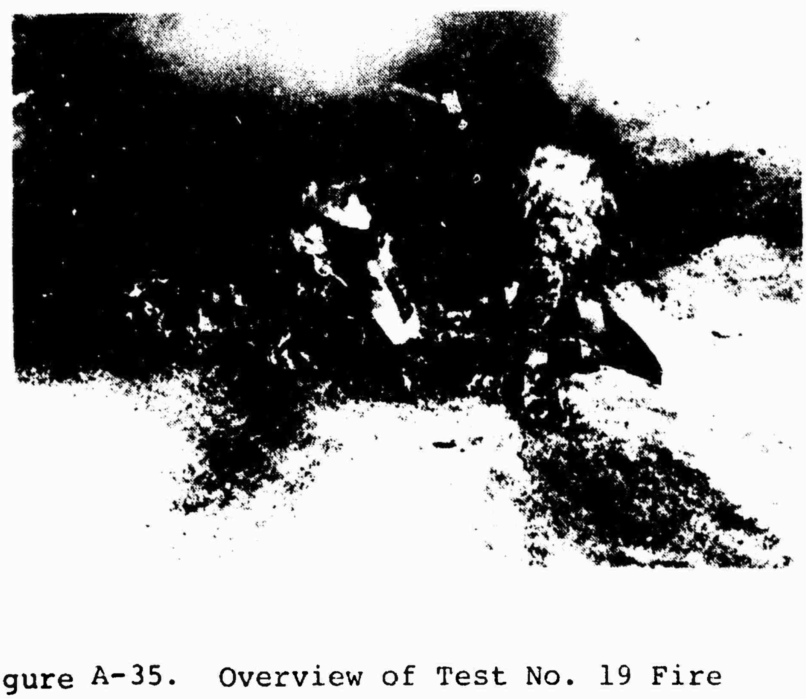

Figure A-35. Overview of Test No. 19 Fire

TEST DATA SHEET

Test 20 | Date 8-30-74 | Ambient 90°F
Fuel Jet A-1 | Wind Calm | Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 2.0 Location Mid-Tank Vertical
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: Full = 100 Gallons Test Tank A
Tank A Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 128 Inches
Length Parallel to tank 144 Inches
Depth 40 Inches

Fire Yes Characteristics:

At detonation there was a large ascending fireball. The descending liquid fuel caught fire like a curtain. The ground fire lasted for 30 minutes.

Test Results:

The explosion blew away the whole top 1/3 of the tank. Both end plates were severed. The area around the fill pipe was blown about 40 feet away. The area of heaviest fuel spray was in line with the ends of the tank. There were areas of extensive perforation along the bottom and both sides of the tank body.

Other Data:

This data was the same as Test No. 15.

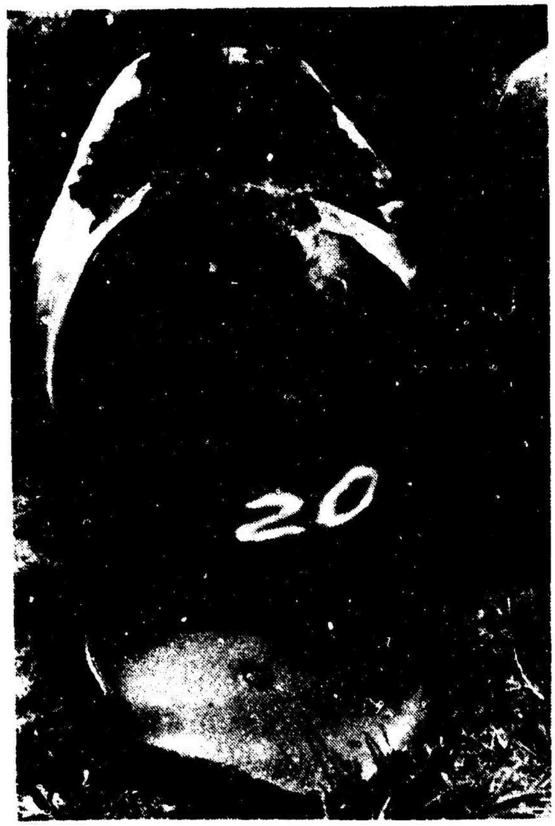

Figure A-36. Closeup of Damaged Fuel Tank
From Test No. 20

Figure A-37. Overview of Crater Fire and Fuel Spray Pattern
From Test No. 20

TEST DATA SHEET

Test 21 Date 8-30-74 Ambient 95°F
Fuel Jet A-1 Wind ________ Sky Clear, Sun

Explosive Charge: End-Tank
Weight (Pounds) 8.75 Standoff (Inches) 9 Location Horizontal
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank ________ Inches
Length Parallel to tank ________ Inches
Depth ________ Inches

Fire No Characteristics: There was a fireball of 2 to 3 seconds duration, but no sustained ground fire.

Test Results:

The explosion sheared off the tank end nearest to the charge. The cylindrical portion of the tank was crimped closed over a distance of 24 inches leaving about 25 gallons of fuel in the tank. The tank came to rest about 30° off vertical with the closed end resting against the backup tank. The tank was totally uncovered.

Other Data:

This distance was the same as Test No. 15.

Figure A-38. Closeup of Damaged Fuel Tank
From Test No. 21

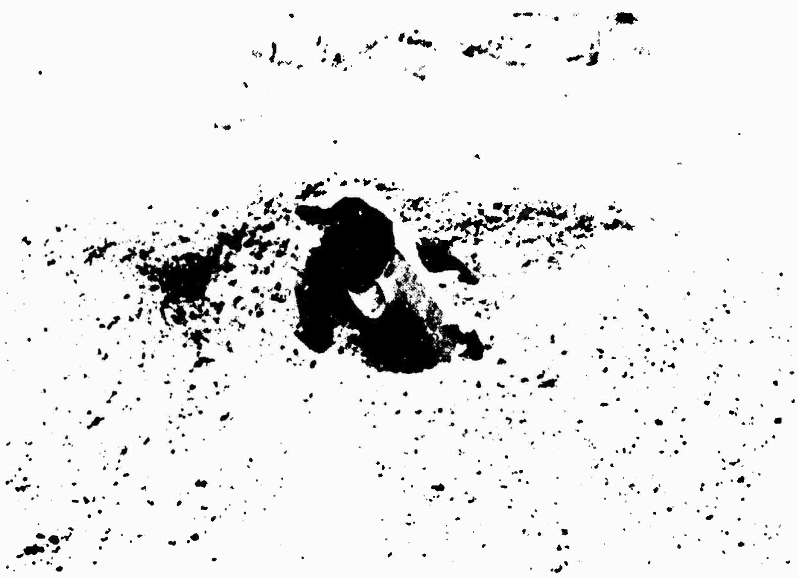

Figure A-39. Overview of Fuel Tank in Crater
From Test No. 21

TEST DATA SHEET

Test 22 Date 9-5-74 Ambient 85°F
Fuel Jet A-1 Wind Calm Sky Partially Cloudy

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 4 Location End-tank Horizontal
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 96 Inches
Length Parallel to tank 108 Inches
Depth 48 Inches

Fire No Characteristics:

Test Results:

The explosion sheared off the near side end of the tank. A strip of steel 4 to 5 inches wide and containing the longitudinal weld was peeled back inside the tank for 3½ feet. The far end of the tank remained buried. About 5 gallons of fuel each was in the tank and crater puddle. The fuel spray area was opposite to the buried end of the tank and covered a fan-shaped area 30 to 40 feet long and 20 feet wide. The crater had very steep (75°) walls.

Other Data:

This data was the same as Test No. 15.

Figure A-40. Closeup of Damaged Fuel Tank
From Test No. 22

Figure A-41. Closeup of Damaged Fuel Tank in Crater
From Test No. 22

TEST DATA SHEET

Test 23 Date 9-12-74 Ambient 90°F
Fuel Jet A-1 Wind 0-3 MPH Sky Partially Cloudy

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 2 Location End-Tank Horizontal
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 150 Inches
Length Parallel to tank 144 Inches
Depth 44 Inches

Fire Yes Characteristics:

At detonation an ascending fireball was seen. Immediately after the fireball, a doughnut-shaped smoke cloud rose above the ground fire. The fire lasted for 10 minutes.

Test Results:

The detonation sheared off the nearest end plate and threw it 30 feet behind and over the test array. The end of the tank was crimped closed, but the far end of the tank remained buried and undamaged. No fuel was left in the tank or crater.

Other Data:

This data was the same as Test No. 15.

Figure A-42. Closeup of Damaged Fuel Tank From Test No. 23

Figure A-43. Overview of Crater Fire and Tank Damage For Test No. 23

TEST DATA SHEET

Test 24 Date 9-12-74 Ambient 90° F
Fuel Jet A-1 Wind 0-3 MPH Sky Partially Cloudy

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 4 Location Mid-Tank 45
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 132 Inches
Length Parallel to tank 120 Inches
Depth 24 Inches

Fire No Characteristics:

Test Results:

The detonation blew the top central portion of the tank through its bottom. Both tanks were sheared off. There was about 10 gallons of fuel left in the tank, but no fuel in the crater area.

Other Data:

This data was the same as Test No. 15.

Figure A-44. Closeup of Damaged Fuel Tank From Test No. 24

Figure A-45. Closeup of Damaged Fuel Tank in Crater
From Test No. 24

TEST DATA SHEET

Test 25 Date 9-12-74 Ambient 90°F
Fuel Jet A-1 Wind Calm Sky Clear, Sun

Explosive Charge:
Weight (Pounds) 8.75 Standoff (Inches) 2 Location Mid-Tank 45°
Length (Inches) 12 Diameter (Inches) 4 Type C-4

Film Coverage: HYCAM @ 500 FPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 102 Inches
Length Parallel to tank 120 Inches
Depth 30 Inches

Fire No Characteristics:

Test Results:

The detonation completely blew the top half of the tank away. It sheared off both end plates and vaporized about one-half of the fuel. There was about 20 gallons of fuel left in the bottom of the tank.

Other Data:

This data was the same as Test No. 15.

Figure A-46. Closeup of Damaged Fuel Tank
From Test Number 25

Figure A-47. Closeup of Damaged Fuel Tank in Crater
From Test Number 25

TEST DATA SHEET

Test 26 Date 9-25-74 Ambient 85°F
Fuel Jet A-1 Wind Calm Sky Heavy Overcast

Explosive Charge:
Weight (Pounds) 15 Standoff (Inches) 16 Location Mid-Tank Horizontal
Length (Inches) 14.4 Diameter (Inches) 4.8 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 2.0

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 192 Inches
Length Parallel to tank 186 Inches
Depth 72 Inches

Fire No Characteristics:

Test Results:

The detonation threw both tanks out of the crater. The test tank landed 30 feet from the center of the crater. It had a 180° vertical split in the center, the fill pipe end plate was sheared off and the other end plate was sheared off about 300°. There was a triangular area of fuel spray perpendicular to the crater with its base on the top of the crater. The test tank itself was partially covered with dirt.

Other Data:

This data was the same as Test No. 15.

Figure A-48. Closeup of Damaged Fuel Tank From Test No. 26

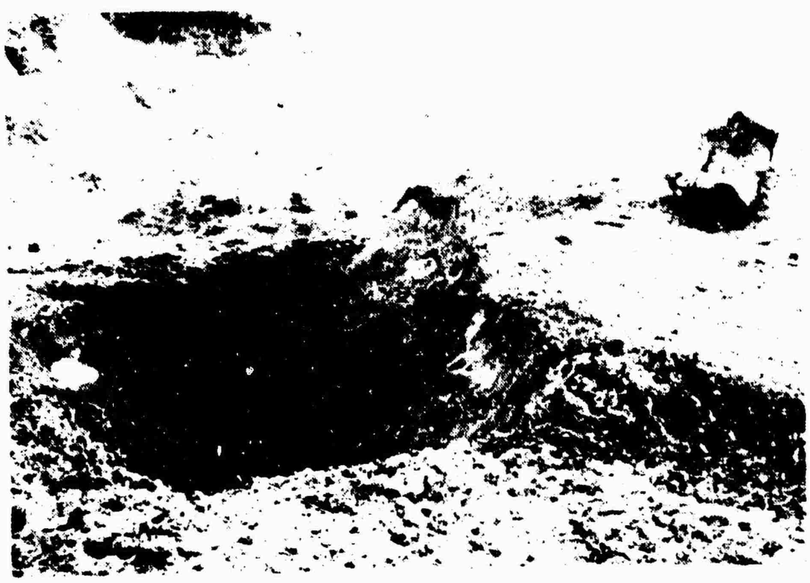

Figure A-49. Overview of Crater and Damaged Tanks From Test No. 26

TEST DATA SHEET

Test 27 Date 9-25-74 Ambient 85°F
Fuel Jet A-1 Wind Calm Sky Partially Cloudy

Explosive Charge:
Weight (Pounds) 15 Standoff (Inches) 13 Location Mid-Tank Horizontal
Length (Inches) 14.4 Diameter (Inches) 4.8 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 156 Inches
Length Parallel to tank 150 Inches
Depth 48 Inches

Fire Yes Characteristics:

There was a sustained fire immediately around the test tank. It lasted for 10 minutes. There was no fire or fuel in the crater.

Test Result:

The test tank was blown out of the crater and landed 20 feet behind the backup tank. Both end plates were blown off of the test tank. The main body of the tank was crushed to one-half its original diameter over most of its length.

Other Data:

This data was the same as Test No. 15.

igure A-50. Closeup of Damaged Fuel Tank From Test No. 27

Figure A-51. Overview of Crater and Remote Fire From Test No. 27

TEST DATA SHEET

Test 28 Date 9-25-74 Ambient 85°F
Fuel Jet A-1 Wind Calm Sky Partially Cloudy

Explosive Charge:
Weight (Pounds) 30 Standoff (Inches) 16 Location Mid-Tank Horizontal
Length (Inches) 18.3 Diameter (Inches) 6.1 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 4.0

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 186 Inches
Length Parallel to tank 168 Inches
Depth 60 Inches

Fire Yes Characteristics:

There was a sustained fire immediately around the test tank. The fire lasted about 10 minutes. There was no fire or fuel in the crater.

Test Results:

The detonation threw the test tank over, and 20 feet behind, the backup tank but left both end plates in the crater. The back central portion of the tank was fractured vertically. The remainder of the tank was crushed flat. The backup tank (D) was lifted 10 inches and crushed over its whole length to about 1-foot thickness. This was the first instance of heavy damage being done to the backup tank.

Other Data:

This data was the same as Test No. 15.

Figure A-52. Closeup of Damaged Fuel Tank From Test No. 28

Figure A-53. Overview of Damaged Tanks and Remote Fire For Test No. 28

TEST DATA SHEET

Test 29 Date 10-11-74 Ambient 85°F
Fuel Jet A-1 Wind 0-5 MPH Sky Partially Cloudy

Explosive Charge: End-Tank
Weight (Pounds) 15 Standoff (Inches) 4 Location Horizontal
Length (Inches) 14.4 Diameter (Inches) 4.8 Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons Test Tank A
Tank A 1/2 Full Tank C Not used
Tank B Not used Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 156 Inches
Length Parallel to tank 168 Inches
Depth 60 Inches

Fire No Characteristics:

Test Results:

The detonation lifted the far end of the tank partially out of the ground, sheared off the near end plate, and split the longitudinal weld area for 3 feet. The split portion was pushed in on itself near the open end of the tank. There was no fuel in the tank or crater.

Other Data:

This data was the same as Test No. 15.

Figure A-54. In Situ Closeup of Damaged Fuel Tank From Test No. 29

Figure A-55. Overview of Damaged Fuel Tank in Crater From Test No. 29

TEST DATA SHEET

Test 30 — Date 10-11-74 — Ambient 85° F
Fuel Jet A-1 — Wind 0-5 MPH — Sky Partially Cloudy

Explosive Charge:
Weight (Pounds) 30 — Standoff (Inches) 24 — Location Mid-Tank Horizontal
Length (Inches) 14.4 — Diameter (Inches) 4.8 — Type C-4

Film Coverage: HYCAM @ 500 PPS Lens 25 MM @ f 5.6

Fuel Level: 1/2 Full = 50 Gallons — Test Tank A
Tank A 1/2 Full — Tank C Not used
Tank B Not used — Tank D Empty

Target Damage Heavy

Crater Data: Length Perpendicular to tank 174 Inches
Length Parallel to tank 180 Inches
Depth 72 Inches

Fire No Characteristics:

Test Results:

The detonation threw the test tank over and 2½ feet behind the backup tank. Both of the end plates remained in the crater. The main tank body was flattened down to 3 inches over its entire length.

Other Data:

This data was the same as Test No. 16.

Figure A-56. Closeup of Damaged Fuel Tank From Test No. 30

Figure A-57. Overview of Damaged Tanks From Test No. 30

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APPENDIX B

MODEL LAW FOR UNDERGROUND STRUCTURES UNDER DYNAMIC LOADS

INTRODUCTION

Most physical systems can be studied by means of scale models whose behavior relates in a known way to that of the prototype. The problem is to write a valid scaling law that accurately displays this similarity. This requires a certain familiarity with the physical concepts involved in the system, plus a degree of mathematical agility.

Certain laws of similitude must be observed to insure that model test data can be applied to the prototype. These laws, in turn, provide a means for designing model tests and for correlating and interpreting test results. The following sections provide background for insight and rationale for use in defining a scaling law for underground structures under dynamic loads.

THEORY OF EARTH SHOCK

Detonation of an explosive charge beneath the earth's surface produces a mass of very high pressure gas that imparts a high radial velocity to the earth particles adjacent to the charge. This particle velocity is evident as a high transient pressure in the medium which is naturally reduced by cooling of the gas through thermal conduction to medium, and through relief of pressure by breakthrough of the gas to the surface or into the surrounding earth. If the charge is buried at large depths with respect to the charge size, a camouflet chamber will be formed beneath the surface, with little gas escaping to the surface, and little crater formation produced. As the burial depth is decreased, more and more earth is ejected from the area of the detonation until an optimum depth is reached so that a crater of maximum size is produced. Thereafter, the crater size is reduced as the burial depth nears the surface.

It is this region of interaction between explosive, the earth surface, and a buried concrete structure that is of interest in this study. Energy produced by the explosive will be directed against the shelter but vented to the earth's surface during crater formation. Redwood describes in detail the conditions at a fluid/solid interface, similar to those existing at earth/concrete interfaces, wherein shock reflections and refractions will be generated. These conditions determine what percentage of the impacting shock wave is transmitted into the underground structure, thereby contributing to damage.

The magnitude of the transmitted pressure wave from an explosive charge is profoundly influenced by the properties of the soil through which it passes. Certain soils, such as wet clay, are very good transmitters of pressure, while other soils such as silty loams are poor transmitters. The transmissibility of soil is expressed quantitatively by the soil constants k, called the initial modulus of elasticity (discussed in detail in the following section). The magnitudes of many phenomena in the medium, such as particle velocity, acceleration, transient motion, and impulse, are found to be proportional to some function of this soil constant, which turns out to be the quantity that is most descriptive of the propagation qualities of the soil. The magnitude of a pressure wave propagated through earth is essentially determined by five factors: the distance from the charge, the character of the soil, the coupling of the explosive energy to the soil, the kind and amount of explosive, and burial depth of the charge.

The general equation found to relate these quantities over a wide range of pressures is given by Equation (B-1). The coupling factor F varies according to the charge burial depth (Figure B-1) while the explosive factor E depends upon the type explosive being considered (Table B-1).

Similarly, the blast impulse in earth is found to be related to the same general parameters as blast pressure as given in Equation (B-2). Here, the explosive factor is identically dependent upon depth of the charge, but explosive factors E' (Table B-2) are slightly different as is the soil constant for impulse. This soil constant may be roughly related to that for pressure, resulting in Equation (B-3).

The mathematical expression for pressure in free earth is:

$$P = F\ E\ k\ Z^{-3} \tag{B-1}$$

where: F = Charge coupling coefficient

E = Explosive factor for pressure

k = Soil constant for pressure

Z = Scaled distance

r = Distance

w = Charge weight.

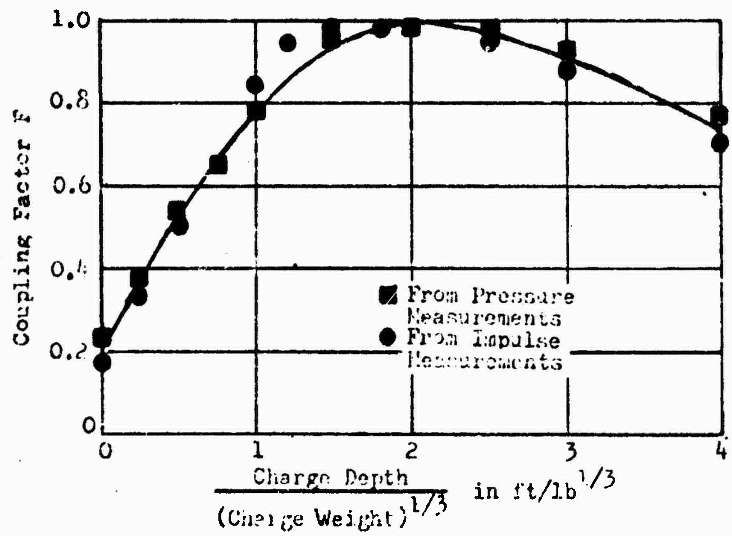

Figure B-1. Explosive Coupling Factor as a Function of Charge Depth in Clay Silt

TABLE B-1. EXPLOSIVE FACTORS FOR PRESSURE

Explosive	Explosive factor E
TNT	1.00
Amatol	1.04
Comp. B	1.04
Tritonal	1.17
Minol 2	1.34
HBX 2	1.39

TABLE B-2. EXPLOSIVE FACTORS FOR IMPULSE

Explosive	Explosive factor E'
TNT	1.00
Amatol	1.04
Comp. B	0.97
Tritonal	1.27
Minol 2	1.38
HBX 2	1.50

TABLE B-3. TABULATION OF CONSTANTS FOR VARIOUS SOILS

Soil Type	Seismic Velocity (fps)		Soil Constant k (psi)	
	min	max	min	max
Top soil (light dry)	600	900	262	590
Top soil (moist, loamy silt)	1,000	1,300	812	1,370
Top soil (clayey)	1,300	2,000	1,420	3,370
Top soil (semiconsolidated sandy clay)	1,250	2,150	1,510	4,150
Wet loam	--	2,500	--	5,600
Clay (dense wet, depending on depth)	3,000	5,900	8,850	34,100
Rubble or gravel	1,970	2,600	6,400	11,100
Cemented sand	2,800	3,200	9,700	12,600
Water-saturated sand	--	4,600	--	22,500
Sand	4,600	8,400	26,200	87,000
Sand clay	3,200	3,800	10,000	13,900
Cemented sand clay	3,800	4,200	17,800	21,700
Clay, clayey sandstone	--	5,900	--	45,000
Loose rock talus	1,250	2,500	1,750	7,000
Weather-fractured rock	1,500	10,000	3,100	140,000
Weather-fractured shale	7,000	11,000	63,000	156,000
Weather-fractured sandstone	4,250	9,000	23,500	116,000
Granite (slightly seamed)	--	10,000	--	160,000
Limestone (massive)	16,400	20,200	390,000	590,000

TABLE B-4. SOIL CONSTANTS FOR IMPULSE FOR VARIOUS SOILS

Soil	Location	k' (avg)
Loess	Natchez, Mississippi	1.60
Clay silt (loam)	Princeton, New Jersey	4.77
Silty clay	Camp Gruber, Oklahoma	5.44
Clay	Houston, Texas	6.64

The mathematical expression for impulse in free earth is:

$$I = E' \; F \; k' \; W^{1/3} \; Z^{-5/2} \qquad \text{(B-2)}$$

where: E' = Explosive factor for impulse

k' = Soil constant for impulse

The general impulse is:

$$I_o = 0.076 \; k^{1/2} \; W^{1/3} \; Z^{-2.6} \qquad \text{(B-3)}$$

The soil factor k has been determined for numerous soil types (Table B-1) by measuring seismic velocities in the soil. A correlation has been found between the soil constant k and the velocity of propagation of a seismic wave in the material to be:

$$k = \rho\mu^2/25 \qquad \text{(B-4)}$$

where:

k = soil constant, psi

ρ = soil density, $lb\text{-}sec^2/in^4$

v = seismic wave velocity, in/sec

The general variability of soil constant to be expected can be seen from the range of the maximum and minimum values for each soil type (Table B-3). This range is probably due to local conditions of moisture content and composition. The largest variable other than the type of soil seems to be its moisture content, a factor that may vary rapidly with depth where shallow water tables are present. Under these conditions, the moisture content and velocity of transmission may vary over a large range near the surface.

Because of this great dependence of shock transmission phenomena on soil properties, a knowledge of these properties is necessary for each set of test parameters used. Unfortunately, direct laboratory determinations of soil properties are seldom possible because sample disturbance often produces irreversible changes in the properties of a soil removed from the ground. However, good sampling techniques and correlations can lead to reasonably reliable test interpretations.

It has also been found that the impulse constant k' can be correlated with soil density and seismic velocity. The degree of correlation is not as good as that for the pressure soil constant but can afford a rough guide to the magnitude of expected impulse. The expression for k' is as follows:

$$k' = 1.15\rho v = 5.75\rho^{1/2}\ k^{1/2} \qquad \text{(B-5)}$$

SCALING

A model law for high explosives can be determined by a consideration of equations describing motion of a shocked fluid. In essence, this law states that "pressure and other properties of the shock wave will be unchanged if the length and time scales are unchanged by the same factor, n, as the dimensions of the explosive loading source", that is:

$$L_p = n\ L_m \qquad \text{(B-6)}$$

$$T_p = n\ T_m \qquad \text{(B-7)}$$

$$W_p = n^3\ W_m \qquad \text{(B-8)}$$

where L, T and W are dimensional symbols for length, time, and charge weight, respectively, and the subscript p denotes the prototype and m designates the model. Since the density scale must therefore be unity, the scaling factor for the mass of the explosive is:

$$M_p = n^3\ M_m \qquad \text{(B-9)}$$

where M is the dimensional symbol for mass.

The same geometric scaling which governs shock transmission process also provides proper modeling for structural response to pressures generated during the blast process. Motion of the structure due to applied blast loads is expressed by Newton's second law $F = M (T)^{-2} L$ and, therefore, it follows that:

$$F_p = n^2 F_m \quad \text{(B-10)}$$

where F is the dimensional symbol for force. In those structures where the mode of action is primarily in the plastic range, similitude between the model and prototype system will be realized when the dimensionless ratio of the external work to the stored strain energy is the same for both systems, i.e., the kinetic energy, associated with the momentum of the structure, imparted by the blast loads will be numerically equal to the strain or potential energy of the structure for both the model and prototype systems.

The kinetic energy may be expressed in terms of the impulse, I, of the blast loads or, $KE = I^2/2M$, where the impulse is a function of force and time. Therefore,

$$(KE)_p = n^3 (KE)_m \quad \text{(B-11)}$$

The potential energy of a structure is numerically equal to the area under its resistance-deflection curve and, therefore, is a function of force and length. Thus,

$$(PE)_p = n^3 (PE)_m \quad \text{(B-12)}$$

On the basis of the above relationships, it may be concluded that the similarity principle which applies to the blast loads applies equally well to the modeling of the structural response to the transient forces generated by the interaction of the blast waves and the structure. Certain limitations do appear in the application of these scaling laws. The rate of strain associated with the structural response of the prototype may differ significantly from that of the model. This variation will depend upon the model size and differences in the materials used in both systems. Another limitation imposed by the scaling laws is due to the invariance of gravitational forces which will distort the scaling effects for parameters such as dead loads and distances traveled by fragments. In blast-resistant design the effects of dead loads and other such physical parameters will usually be small in comparison to the effects of the blast environment and, therefore may usually be neglected in the model design.

With the "ideal" scale for length, time and force (or mass), it is possible to derive an ideal scale for each specific parameter involved in the model design. These scales are obtained by proceeding in the manner employed above for kinetic and potential energies. A summary of the more pertinent quantities and their ideal scales is given in Table B-5.

EXAMPLES

Given below are some examples of the use of the scaling law proposed in the "Scaling" portion of this appendix.

A. Point Loading of a Curved Beam

Analysis of the pin-jointed structure, shown in Figure B-2, involves the determination of horizontal thrust, H, before stresses and deflection can be calculated. The equation for H is:

$$\frac{H}{P} = \frac{\left[2 \sin\alpha + 3 \cos 2\alpha - (\pi - 2) \sin 2\alpha - 1\right]}{\left[2 (\pi - 2\alpha) (1 + 2 \sin^2\alpha) - 6 \sin 2\alpha\right]} \qquad \text{(B-13)}$$

The equation for deflection is

$$y = Y_s - \frac{H r^3}{EI} \left[\sin\alpha + 0.7500 \cos 2\alpha - 0.2500 (\pi - 2\alpha) (\sin 2\alpha) - 0.2500\right] \qquad \text{(B-14)}$$

where:

$$Y_s = \frac{Pr^3}{EI} \left[(\pi - 2\alpha) (1 - 2 \cos^2\alpha) - 8 \cos\alpha + 3 \sin 2\alpha\right] \qquad \text{(B-15)}$$

Bending moment at the section defined by θ is

$$M = Hr (\sin\theta - \sin\alpha) - Pr (\cos\alpha - \cos\theta) /2 \qquad \text{(B-16)}$$

Figure B-3 shows prototype and model structures. Angle scale is unity; hence, θ and α are the same for both the prototype and the model. Scale on length is n which, for illustrative purposes, in Figure B-3 is shown as 2, i. e.,

$$r_p = n\, r_m \qquad \text{(3-17)}$$

TABLE B-5. COMPUTATIONS OF IDEAL SCALES

Quantity	Symbol	Typical Units	Ideal Scale	
Length	l	ft	l_p/l_m	$= n$
Depth	d	ft	d_p/d_m	$= n$
Area	A	ft^2	A_p/A_m	$= n^2$
Mass	m	$lb\text{-}sec^2/ft$	m_p/m_m	$= n^3$
Area of Rein.	A_s	$in.^2$	$(A_s)_p/(A_s)_m$	$= n^2$
Area of Rein/ft	A'_s	in	$(A'_s)_p/(A'_s)_m$	$= n$
Unit Resistance	w	$lb/in.^2$	w_p/w_m	$= 1$
Total Resistance	R	lb	R_p/R_m	$= n^2$
Weight	W	lb	W_p/W_m	$= n^3$
Distance	r	ft	r_p/r_m	$= n$
Scaled Distance	Z	$ft/lb^{1/3}$	Z_p/Z_m	$= 1$
Total Impulse	I	lb-ms	I_p/I_m	$= n^3$
Unit Impulse	i	$lb\text{-}ms/in.^2$	i_p/i_m	$= n$
Scaled Impulse	$\bar{i}$	$lb\text{-}ms/in.^2/lb^{1/3}$	$\bar{i}_p/\bar{i}_m$	$= 1$
Pressure	p	$lb/in.^2$	p_p/p_m	$= 1$
Kinetic Energy	KE	ft-lb	KE_p/KE_m	$= n^3$
Density	ρ	$lb\text{-}sec^2/ft^4$	ρ_p/ρ_m	$= 1$
Elastic Modulus	E	$lb/in.^2$	E_p/E_m	$= 1$
Deflection	δ	in	δ_p/δ_m	$= n$
Moment	M	ft-lb	M_p/M_m	$= n^3$
Moment/ft	$\bar{M}$	lb	$\bar{M}_p/\bar{M}_m$	$= n^2$
Shear	V	lb	V_p/V_m	$= n^2$
Shear/ft	$\bar{V}$	lb/ft	$\bar{V}_p/\bar{V}_m$	$= n$
Stress	σ	$lb/in.^2$	σ_p/σ_m	$= 1$
Strain	ε	-	$\varepsilon_p/\varepsilon_m$	$= 1$
Velocity	v	ft/sec	v_p/v_m	$= 1$
Time	t	sec	t_p/t_m	$= n$
Moment of Inertia	I	in^4	I_p/I_m	$= n^4$
Frequency	f	cycles/sec	f_p/f_m	$= 1/n$
Acceleration	a	ft/sec^2	a_p/a_m	$= 1/n$

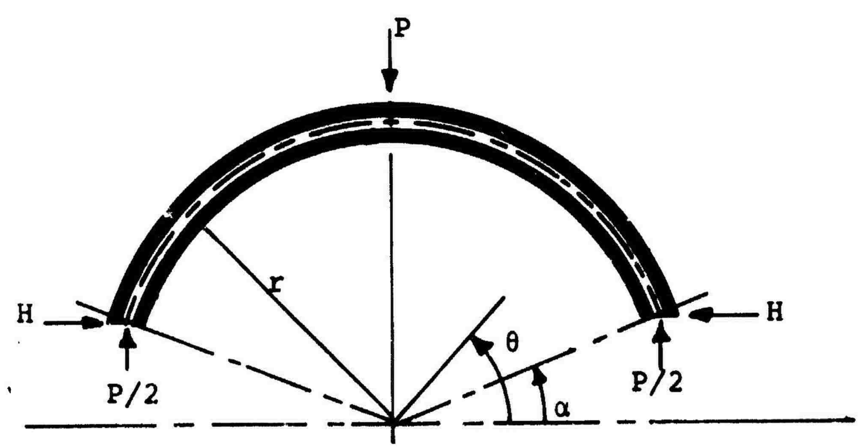

Figure B-2. Pin-Jointed Circular Arch

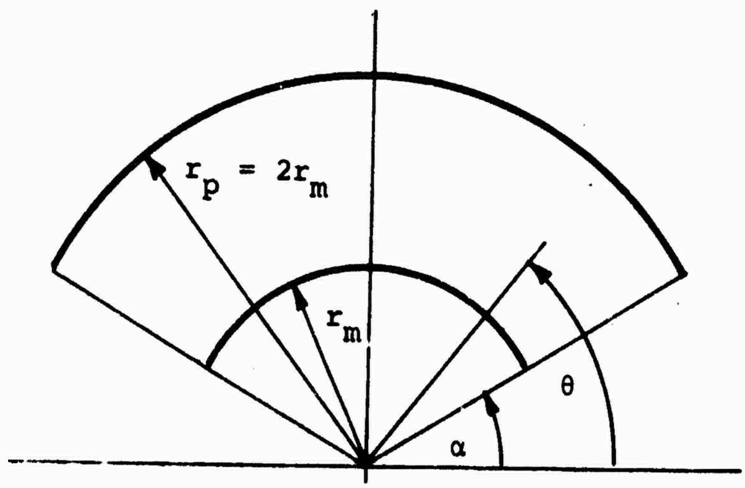

Figure B-3. Prototype and Model of Arch

Horizontal thrust H is given by

$$H_p = K_o P_p \tag{B-18}$$

$$H_m = K_o P_m \tag{B-19}$$

where K_o is a function of θ and α(see Equation B-13)

Scale between forces is

$$P_p = N^2 P_m \tag{B-20}$$

or

$$H_p = K_o P_p = K_n{}^2 P_m = n^2 H_m \tag{B-21}$$

The term Y_s is given by:

$$Y_{sp} = K_1 \frac{P_p \, r^3{}_p}{E_p \, I_p} \tag{B-22}$$

$$Y_{sm} = K_1 \frac{P_m \, r^3{}_m}{E_m \, I_n} \tag{B-23}$$

Assuming that beams are made of the same material:

$$E_p = E_m = E \tag{B-24}$$

and rectangular beams are used so that

$$I_p = b_p h_p{}^3/12 \tag{B-25}$$

$$I_p = b_m h_m{}^3 /12 \tag{B-26}$$

then

$$I_p = (n\ b_m)\ (n\ k_m)^3\ /12 = n^4 b_m h^3/12 \tag{B-27}$$

$$= n^4 I_m \tag{B-28}$$

This gives

$$Y_{sp} = K_1 \frac{P_p r_p}{E I_p} = K_1 \frac{n^2 P_m (n r_p)^3}{E n^4 I_m} \quad \text{(B-29)}$$

$$= n Y_{sm} \quad \text{(B-30)}$$

similiarly

$$Y_p = n Y_m \quad \text{(B-31)}$$

$$M_p = n^3 M_m \quad \text{(B-32)}$$

Maximum stresses in a curved beam due to a bending moment, M, are given by[5]

$$\sigma \max = \frac{M h_1}{A \bar{y} a} \quad \text{(B-33)}$$

$$\sigma \min = \frac{-M h_2}{A \bar{y} c} \quad \text{(B-34)}$$

where

A - cross-sectional area

a - inner radius of beam

c - outer radius of beam

h_1 - distance from neutral axis to σmax

h_2 - distance from neutral axis to σmin

$\bar{y}$ - distance from neutral axis to beam centroid.

Using the scale to compute σ_{max} for the prototype and model gives:

$$\sigma \max(p) = \frac{M_p \, h_{1p}}{A_p \, \bar{y}_p \, a_p} \qquad \text{(B-35)}$$

$$= (n^3 M_m) \; (n \, h_{1m}) / (n^2 A_m) \; (n \, \bar{y}_m) \; (na_m) \qquad \text{(B-36)}$$

$$= \frac{M_m \, h_{1m}}{A_m \, \bar{y}_m \, a_m} \qquad \text{(B-37)}$$

$$= \sigma \max \, (m) \qquad \text{(B-38)}$$

This shows that stresses will be the same in both cases if the model is made of the same material as the prototype and if the load is scaled as n^2.

B. Distributed Loading of a Curved Beam

Loading of a curved beam by a distributed load, g, is generally defined in terms of load per unit length along the beam. For a uniformly loaded, pinned beam the bending moment is proportioned to this distributed load.

$$M = K_2 \, qr^2 + K_3 \, Rr \qquad \text{(B-39)}$$

where

K_2, K_3 - proportionality constants

R - support reactions

If the distributed load is due to pressure, then

$$q = ps \qquad \text{(B-40)}$$

w - beam width

The first term of the RHS of Equation (B-39) is then written as

$$M_q = K_2 \, q \, r^2 = K_2 pw \, r^2 \qquad \text{(B-41)}$$

Since this reaction contribution to bending moments can be treated as the point loads of the previous example, only M_q will be considered here.

For the prototype and model,

$$M_{qp} = K_2 \, P_p \, W_p \, r_p^{\,2} \tag{B-42}$$

$$M_{gm} = K_2 \, P_m \, W_m \, r_m^{\,2} \tag{B-43}$$

or

$$M_{qp} = K_2 \, P_p \, W_p \, r_p^{\,2} = K_2 \, P_m \, (n \, W_m) \, (n \, r_m)^2 \tag{B-44}$$

$$= n^3 \, M_{qm} \tag{B-45}$$

Hence, if pressure applied to the model is the same as that expected by the prototype, moments will scale with the stresses of both reaching the same value. See Equations (B-35) to (B-38).

C. Pressure Loading Due to Blast

Pressure exerted on the front face of a structure is approximately twice that measured in free earth. Pressure on a massive target in earth can be represented by the following expression, provided normal explosives are used at depths of the order $2W^{1/3}$ and at distances from the target between $2W^{1/3}$ and $15W^{1/3}$, all measured in feet:

$$P_r = 2 \, k \, E \, Z^{-3} \tag{B-46}$$

where P_r is the reflected pressure and the scaled distance is

$$Z = r/W^{1/3} \tag{B-47}$$

For the scale law selected Z, and hence the reflected pressure, will be the same for the prototype and model, i.e.,

$$Z = r_p/W_p^{\,1/3} = n \, r_m/ \, (n^3 \, W_m)^{1/3} \tag{B-48}$$

$$= r_n/W_m^{\,1/3} \tag{B-49}$$

Using scaled charge weights; i.e.,

$$W_p = n^3 \, W_m \tag{B-50}$$

at the scaled distances

$$r_p = n\ r_m, \tag{B-51}$$

the resultant stress levels in the beam will be the same.

Consider the case where an 8-pound charge is detonated 6 feet from a scale model structure. The scaled distance is

$$Z = 6\ /\ (8)^{1/3} = 3$$

The prototype will experience the same stress and strains as the model if a 1000-pound charge is detonated 30 feet from it; i.e.,

$$Z = 30\ /\ (1000)^{1/3} = 3$$

THE MODEL LAW

The model law, when referred to in connection with physical tests, is a term generally applied to a set of rules derived through dimensional reasoning by which the results of a set of properly designed experiments can be extended to larger or smaller scales of phenomena. The terms "scale effect" has been somewhat loosely applied to any deviations from the model law that arise in an analysis of experimental results derived from models. The presence of such effects, which apparently do occur in some classes of experiments greatly complicates the analysis of the results. Fortunatley no such effects have been detected in underground explosion testing, and the model law results can be extended with an accuracy as good as that of the original measurements.

If it is assumed that the velocity of propagation of the effect on an explosion in earth depends only on the stress and not on such quantities as the rate of deformation, then the effect of an increase in all dimensions of the experiment by the length scale factor n results in an increase of the time of propagation to an equivalent point by the same factor n. It is then possible to make a table (Table B-5) in which any quantity such as pressure, impulse, velocity, etc. is represented by its dimensional components of mass M, length L, and time T, and to arrive at an expression for the relative magnitude of this quantity in the new system which is expanded in length scale by the factor n. In present experiments $W^{1/3}$, the cube root of the weight of explosive charge,in pounds, has been selected as being a length characteristic of the scale of the experiment. This may seem dimensionally misleading,but it merely means that there has been chosen for reference a unit of length whose cube is proportional to the weight or volume of the charge. Then if an experiment is performed with a charge-weight of W_1 pound and it is required to know the effects that would occur with a charge-weight of W_2 pound, the scale ratio $n = (W_2/W_1)^{1/3}$, and at the distance n, the magnitudes of the quantities in question can be determined from the original measurements at distance r multiplied by the factors given in the table. The model law, of course, tells nothing of the manner in which the quantities vary with distance but states only that if the effect is of magnitude E_1 in the experimental system at a distance r from the charge, then in the new system the effect will be AE_1 at a distance nr from the charge, A, depending on the quantity in question and being given in Table B-5.

An example that illustrates the use of the model law is the comparison of the peak pressures produced by the explosion of 1 and 1,000 lb of the same explosive. It is assumed that experiment has shown that at a distance of 4 feet from the 1-lb charge the peak pressure is 80 psi. The length-scale ratio between the two cases is $(1{,}000\text{-lb})^{1/3} = 10$, and Table B-5 shows that the scale factor for pressure is 1; consequently, at a distance of 40 feet (=nr) from the 1,000-lb charge the peak pressure is again 80 psi. This is equivalent to the statement that, if $r/W^{1/3}$ is the same for the two cases, then pressure is the same.

A comparison of the impulse per unit area, I, for these two weights of explosive at the scaled distances 4 and 40 feet is made in the same way, except that, from Table B-5 the scale factor for impulse per unit area is n(=10). Thus, if the impulse per unit area from a 1-lb charge at 4 feet is found to be 0.2 psi-sec, then at 40 feet from a 1000 lb charge the impulse per unit area is 2 psi-sec. This comes about by virtue of the fact that, although the peak pressures at these scaled distances are the same, the time scale of the phenomena is multiplied by 10, the scale factor, so that the duration of the pressure is increased ten-fold. The impulse, being proportional to the product of pressure and time, must then be increased by a factor of 10 as indicated.

It will be noted that most of the experimentally determined quantities can be represented by empirical equations which have as coefficients a constant, and various combinations of the parameters k, W, p, r, and Z.

The manner in which these parameters enter into the empirical equations can be determined very simply by equating the dimensions on both sides of the equality sign. The variables can be determined from physical considerations, but the manner in which they enter the equations needs to be tested against the experimental data in each case and correlated with the first order of approximation. The test for correctness **consists** in determining to what extent the dimensionless constant in the equations really are constant for widely varying values of the parameters.

With regard to the target and damage relations to the model law, one of the primary objectives of the program is to determine the accuracy of the model law as applied to target damage. The chief cause of the initial uncertainty is the fact that there are certain things in nature that do not scale, the chief offender being the effect of gravity. By changes of density of component materials, efforts to overcome this defect can be made, but it is not easy to find structural materials of comparable strength and with greatly different densities. Consequently, if gravity is a controlling factor in an experiment, modification of the model law must be made. It has been found experimentally, as had been inferred but not proved, that the impulsive forces involved in the damaging of a structure are very large compared to gravity forces, so that essentially no deviation from the model law was detected. The conclusion is then that the structural dimensions can be scaled, at least over a factor of 5 and probably 10, without encountering any deviation from the law as far as explosive damage is concerned.

REFERENCES

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